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EVALUATION OF QUALITY PARAMETERS IN WATER RESOURCE PLANNING. A STATE-OF-THE-ART SURVEY OF THE ECONOMICS OF WATER QUALITY

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PREPARED FOR

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This report reviews water quality from the standpoint of determining the influence of water contaminants on various use of water, the technology and cost of water supply purification, the technology and cost of waste and recycling water purification, the benefits from enhanced water quality, economic techniques for optimal water supply purification and allocation, and economic techniques for optimal waste and recycling water purification. The intent of the report is to provide Corps of Engineers and other planners

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with a summary and critique of the literature and a synopsis of relevant methodology which relates water quantity and water quality. Economic cost and benefit calculations are stressed along with optimizing procedures.

EVALUATION OF QUALITY PARAMETERS
IN WATER RESOURCE PLANNING

A State-of-the-Art Survey of
the Economics of Water Quality

A Report Submitted to the:
U. S. Army Engineer Institute for Water Resources
Kingman Building
Fort Belvoir, Virginia 22060

Under Contract No. DACW01-73-C-0043

by

Eric D. Bovet

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PREFACE

Acknowledgments

Sincere appreciation is expressed for the assistance and guidance received from a large number of individuals and organizations while gathering and evaluating data for this report. A debt of gratitude is owed, in particular, to A. V. Kneese, Resources for the Future; Professor S. Hanke, Johns Hopkins University; W. L. Patterson and R. F. Banker, Black & Veatch, Consulting Engineers; Julian M. Greene, Ernst & Ernst; and to officials of a number of government and private agencies.

D. P. Sheer, a graduate student at Johns Hopkins University, assisted in preparing or monitoring portions of the text, and Professor D. P. Loucks, Cornell University, was retained as a Consultant for a detailed review of the completed report.

Structure and Scope of the Report

While preparing material for the economic evaluation of water quality, it became apparent that a substantial substratum of water quality dimensions were in need of description, definition, and quantification.

The following concepts were defined and, to the extent feasible, quantified: the qualitative characteristics of surface water resources, the origins of water contamination, water quality parameters, total water

quality, damages from the use of water of impaired quality, water quality tolerances and standards, and alternative technologies effective in upgrading water quality. This substratum of concepts is defined in Chapters I and II, and in parts of Chapters IV and V. Economic considerations based on these definitions fill the balance of the report; water quality models are discussed in Chapter III, costs are tabulated in Chapters IV and V, benefits in Chapter VI, and various economic techniques for optimal water purification and allocation are described in Chapters VII and VIII.

Not all aspects of water quality are evaluated in this report. Those of secondary or incidental interest to Corps of Engineers planners were omitted for brevity: groundwater, estuaries, hydroelectric power, navigation and spills, floods and droughts, irrigation, and acid mine drainage.

Conclusions

1. The current state-of-the-art of water quality economics, as represented by publications released during the six-year period ending in the middle of 1974, provides a wealth of useful data and techniques which the Corps of Engineers can use and apply in solving water quality problems.

2. Chief among these are: water user tolerances to water contaminants, water quality standards by uses, damages incurred by users of water of substandard quality, water quality benefits, the technology and cost

of upgrading water quality, water quality models, and various optimization techniques for purifying water and allocating water supply.

3. Among water purification techniques which may lend themselves to increased Corps application are: artificial instream aeration, pumped quality storage, raw water desalination, by-pass piping of wastewater to the ocean, longitudinal or diurnal staggering of outfalls, stormwater reuse, collective wastewater treatment and/or desalination, lake water quality management, the control of excess vegetation, and lagoon construction for various purposes.

4. Nevertheless, the multifarious facets of water quality are incompletely assessed in the literature. Existing contributions are somewhat disparate and for the most part restricted in scope. Because they leave many areas insufficiently investigated, they are difficult to assemble into adequate and meaningful aggregates.

5. What is mostly lacking is a systems approach comprising economic techniques broad enough to cope with all essential water quality dimensions of a typical water allocation and/or instream water management situation.

Recommendations

The following topics are recommended for further research:

1. Levels of tolerance of various water users to specific contaminants. Some are shown in Chapter II; others are available in the "Green Book." Additional tolerance data are needed, so that critical water

quality parameters can be identified for each use. Among other benefits, such data would provide the advantage of determining the feasibility of cascading water reuse.

2. Damages to water users from excessive concentrations of specific contaminants. Dollar costs related to concentrations above tolerance levels are needed for setting water quality standards and for measuring benefits of damages avoided.

3. Capabilities of water treatment processes for removing specific contaminants. It would be desirable to have a tabulation of percent removal of some sixty water quality parameters by about twenty water treatment processes. From such a tabulation could be selected alternate water treatment processes which, in combination, can upgrade water of a given quality to levels tolerable in a given use.

4. Water quality enhancement costs. A price tage needs to be attached to each water treatment process and combination of processes. Costs should be computed for a wide range of flows. -- Water suitable for a given use can always be obtained -- at a price. What is that price? By determining the spread between contaminant concentrations in a given water resource and concentrations tolerated in given water uses, one obtains a list of critical contaminants which must be removed. By establishing the damages incurred when using the water resource without any treatment, and computing the combination of treatment processes

capable of removing the critical parameters at least cost, one obtains data whereby damages plus costs can be minimized.

5. Measurement of water quality benefits. This is an area in need of much more research. Damages must be measured; willingness to pay must be estimated; new approaches for quantifying heretofore imponderable benefits must be developed. Project design and justification rests on comparative costs, damages, and benefits.

6. Checklist of data required for solving a typical water quality problem. Algorithms and checklists for solving standard types of water quality problems should be developed with a view to minimizing investigation time and costs.

7. Periodic revisions of water quality standards. If marginal benefits and marginal costs are used in determining optimal water quality standards, these standards should be revised whenever substantial fluctuations in benefits or costs occur. However, since large and irreversible capital investments are needed to comply with water quality standards, periodic revisions should be announced in advance for planning purposes.

8. An integrated systems approach for optimizing essential water quality parameters in a typical water allocation or instream water management problem. Elements of such an approach exist today; what is missing is an algorithm for handling simultaneously a large number of variables for reaching an over-all optimal solution.

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CHAPTER I. SURFACE WATER RESOURCES AND THEIR CONTAMINANTS

This first chapter briefly reviews approaches for analyzing and describing qualitative phenomena in a surface water body. The origins of water contamination are listed. Contaminants are categorized.

A. Surface Water Resources

Surface water resources can be divided into four types, only two of which are covered in this Manual. Rivers, streams, and canals are the first category; lakes, impoundments, and reservoirs, the second; not included here are estuaries, or coastal sea waters.

1. Rivers, Streams, and Canals

In an attempt to observe and describe water quality and quality changes in a flowing water body, a stream has commonly been divided into successive reaches. These are sections of the stream which, when linked together, extend from its source to its mouth, or over any portion of its course. Reaches can be uniform in length, as for example one mile apart; or their length may vary according to significant hydrologic events such as wastewater outfalls. Reaches are also identified as links, in which no hydrological change takes place, and nodes, in which a confluent flows into the stream or the stream divides. Nodes can be used for important outfalls.

Canals, except sea-level channels which are stationary, differ from streams primarily through lower flow velocity, the regularity of their banks, and sometimes their use (navigation, open sewer, etc.). Locks, where gradients are involved, may affect stream flow.

The geometry of rivers and canals which, according to Chen and Orlob (1), is of interest from a qualitative standpoint, includes length, width, depth, and a friction factor affecting flow. The hydrology comprises flow, inflow, outflow, overflow, tide, and waste discharges.

2. Lakes, Impoundments, and Reservoirs

In stationary and semi-stationary water bodies, water quality is influenced by temperature, density, bottom condition, currents, and wind. Quality tends to be homogeneous throughout a horizontal layer, but varies with depth. This is stratification. The temperature gradients in successive strata may become inverted with the change of seasons.

When analyzing qualitative phenomena in lakes and reservoirs, it is customary to divide the water mass into horizontal slices. Two or three slices may be inadequate. A multi-layered system is most apt to portray qualitative conditions and changes.

The geometry of a lake includes surface area, side slope, elevation, volume, and depth. The hydrology adds inflow, outflow, overflow, and waste discharges.

Common to rivers and lakes are water-quality-affecting meteorological observations, such as air temperature, atmospheric pressure, cloud cover, evaporation, latitude, precipitation, short-wave radiation, solar radiation, wind direction and wind velocity.

By adding water quality parametric data to the above general factors, a water quality study or model of a river or lake can be developed. A number of such studies and models have been constructed. They are reviewed in Chapter III.

B. Origins of Water Contamination

Essentially three sources of water contamination contribute to the impairment of surface water quality: the hydrological and meteorological source ("the elements"), the vegetable and animal source, and the human source (including industry). A knowledge of the principal origins of water contamination may enable the planner to eliminate or reduce a load of impurities before it impairs a water body.

1. Hydrological and Meteorological Origin

Water contamination of hydrological and meteorological origin results from precipitation, wind, sun, and the atmosphere, and from underground contamination. Rain swells flowing and stationary water bodies directly, and indirectly through land precipitation runoff.

The direct route may purify surface water by dilution. The indirect route is apt to impair water quality because of the sediment from land erosion, and the many impurities accumulated on the earth's surface. Rain itself may be contaminated. In a two-year experiment involving rain and stream sampling in New Hampshire's White Mountains, Fisher et al. (2) established that precipitation provides most of the 30-50 kg of sulfate per hectare and 20-40 kg of silica per ha carried annually by three tributaries of Hubbard Brook.

Rain falling on built-up and urban areas is polluted by oil and other wastes clinging to streets and highways; the polluted water is caught by storm sewers where these exist, often being discharged untreated into water bodies. Joint sewer systems carry the rain water to treatment plants with limited capacities, compelling the diversion of overflows, now contaminated with raw sewage, around treatment plants for direct discharge into rivers, streams, and lakes.

Floods intensify the contamination through erosion, but also because flooded areas may have been fertilized and sprayed with pesticides, the runoff being charged with nutrients and toxic compounds.

Snow and ice, acting as water reservoirs in winter, empty themselves over a short period in spring. Impurities accumulated throughout the winter months are released at once, when the soiled snow melts, suddenly impairing the quality of receiving waters.

By directing the path of clouds, wind affects the precipitation pattern. It also erodes the earth's surface, and transports sand, dust, and other impurities (as in dust storms) for many miles. A portion of these impurities, when it rains, is washed into water bodies. A dry wind accelerates evaporation from lakes, reservoirs, and streams. Finally, wind transports radioactive fall-out, which later is carried by rain into flowing or stationary water resources.

The sun is the principal agent of evaporation from open water surfaces. It withdraws almost pure water from rivers and lakes, thereby concentrating such impurities as are left behind. The sun also affects water temperatures, thereby altering waste-assimilative and other processes.

Atmospheric temperature affects water temperature through surface heat exchange. Thus, it changes the saturation point of dissolved oxygen and other solutes. High atmospheric temperatures retard the dissipation of thermal pollution of waterways.

Underground contamination includes the mineralization of springs located in riverbeds or lakes. Salt water intrusion into coastal aquifers is another source of pollution which, at times, may find its way to surface water bodies. Seepage of untreated or insufficiently treated sewage and other wastewater may also take underground routes to surface waters.

2. Vegetable and Animal Origin

This represents an important source of water contamination, perhaps greater than that of human origin -- not in all regions or locations, but for the United States as a whole. Briefly reviewed here are viruses, bacteria, algae, phreatophytes, nutrients, fertilizers, hypertrophication, irrigation return flows, wild animal wastes, and feedlot effluents.

Bacteria and algae are natural, normal, and desirable forms of aquatic life. In fact, minerals and toxic substances that kill or inhibit these may be deleterious to the aquatic environment. The waste-assimilative capability of a water body depends on the presence of aerobic digestion agents. Algae are the greatest single source of oxygen in nature.

The tolerance of animals and man to specific viruses and bacteria is insufficiently known. Coliform counts are relied upon to warn of possible harm, on the assumption that pathogenic species are present in approximately constant proportions to coliforms -- a potentially dangerous assumption.

Sometimes, particularly where human culture has taken hold, algae tend to exceed useful growth levels, invading water bodies to the point of becoming a nuisance. This is hypertrophication. Other

plants, designated phreatophytes, take over the edges of ponds and riverbanks. They waste surface or groundwater resources through evapotranspiration. Water pollution from excessive growth of algal blooms and phreatophytes can assume almost unmanageable proportions. Algae respond to nutrients, fertilizers, phosphates and nitrates. According to Grundy (3), about 2.2 billion pounds of phosphates enter the aquatic environment annually, from the use of detergents alone. This represents 30-40% of all the phosphorus entering our waters.

There exist conflicting views on the chief nutrients responsible for hypertrophication. Phosphates and nitrates have generally been blamed for it. Not these, but photosynthetic carbon dioxide in alkaline waters, are the nutrients of algal growth, say others.

In 1967, Lange (6) explained the symbiotic growth of planktonic blue-green algae with bacteria. Algae exist in a mutually supportive association with bacteria: algae utilize carbon dioxide and sunlight to produce organic matter and oxygen by photosynthesis; bacteria use oxygen in the decomposition of organic matter to produce carbon dioxide. It is, in Lange's view, the presence of large amounts of organic material in water that makes the production of huge amounts of carbon dioxide available for algal growth. Very minor amounts of phosphorus are sufficient for algal growth, but algal growth can be starved by removing organic materials.

The 12th Sanitary Engineering Conference on Nitrate and Water Supply (5) brought out that sewage treatment plants are designed for the removal of suspended solids and BOD, not nitrogen. Urbanization, harvesting of trees, and paving hasten the movement of nitrates from land to water. Infants are particularly susceptible to concentrations of nitrate in water; excessive ingestion may lead to methemoglobinemia, a potentially fatal disease.

Irrigation return flows are diffuse discharges containing nutrients from fertilizers, toxic compounds from pesticides, and also salts leached from the soil by irrigation water. Gordon (7) advocates the sprinkler method of irrigation over the more common flood irrigation method. This would reduce salt leaching to one-half.

Wild animal wastes, as a source of water contamination, are difficult to assess. Despite conflicting opinions, they may still represent the largest single source of waste loads in U. S. streams and lakes. Wolman (8) lent support to this thinking in an article entitled "Blame Nature for Impure Water." In his words, "those who seek to recapture water of pristine purity are unrealistic. . . Rivers were dirty long before man arrived on the scene." Henderson (9) contends that a 3-lb duck has a fecal coliform production rate equal to 5.5 adult men; ducks alone may thus represent, in fecal coliforms produced, a "population equivalent (PE) of 170-850 million persons. This must be compared with discharges by the non-sewered population of the U. S., or a PE of 35 million men.

Feedlot effluents are important because of the increasing concentration of large herds or flocks. Liquid animal wastes amount to over 600 million tons annually. Land application seems the most effective means of animal waste disposal.

3. Human and Industrial Origin

Water contamination from human origin takes on many forms. Succinctly discussed here are human wastes, solid refuse, litter, residual wastes, recreational and watercraft wastes, erosion, sedimentation, de-icing, industrial wastewater, thermal pollution, and radioactive contamination.

Municipal sewage from domestic, commercial, industrial and institutional origin, when incompletely treated, and rural wastes, account for much of the pollution which the U. S. government is trying to abate. Storm runoff, contaminated with oil, adds heavy though intermittent waste loads. Solid refuse and litter, upon being soaked by rain, affect the quality of receiving waters.

Residual wastes are those peculiar to water treatment operations. A raw water treatment plant, a sewage treatment plant, a desalination plant, all generate sludge, brine, or other residues. Some are disposed of in streams or lakes, or on land whence precipitation runoff carries it into a water body. Incineration with safeguards against air pollution seems the most acceptable disposal method for sludge. Brine is not amenable to that technique.

Recreational and watercraft wastes raise the question of how safe it is to use water supply reservoirs for swimming and other recreational purposes, and the need for self-contained marine sanitary facilities.

Erosion, sedimentation and de-icing are additional sources of water contamination. Man-made erosion, incident to land clearing, highway and building construction, adds silt and sand, gravel and rocks, branches and trees, to the natural load of sediment in rivers and lakes. Nine million tons of salts are spread annually on the nation's highways, up to 100 tons per road-mile, for de-icing; most of these salts end up in streams and lakes.

Water in industry is used for boiler make-up, processing, incorporation in the product, cooling, sanitary and fire fighting purposes. Wastewater from processing is troublesome, every imaginable form of pollution being produced, including toxic and mineral wastes.

Cooling water effluents from power and other industrial plants can be of benefit to citrus groves, and by keeping navigable channels and ports free of ice in winter. Otherwise, potentially deleterious thermal pollution is generated. It can be abated at reasonable cost.

As more nuclear power plants are built, possible radioactive contamination of American water resources becomes a serious hazard. It

is both cumulative and irreversible. The threat will continue till clean reactors become available, hopefully before the end of this century.

C. WATER CONTAMINANTS

Once contaminants from many origins have found their way into a stream or lake, they may lose their identity and are subject to chemical reaction, dilution, waste-assimilation, or gradual self-purification. The resultant water quality balance varies with flow and outfalls, both independently time-variable. Water quality is a stochastic concept which can be expressed as varying within a range of values, or as falling below a specified value a given percent of time.

Seven types of water quality parameters suffice to account for most contaminants:

1. Physical constituents (suspended solids)
2. Biological constituents
3. Chemical constituents (dissolved solids and gases)
4. Color, odor, and taste
5. Toxic constituents
6. Thermal contamination
7. Radioactive contamination

1. Physical Constituents

These include temperature, turbidity, and suspended solids. The latter comprise sediment and other organic or inorganic matter

in suspension. Suspended solids are measured in tons per day or per year, or in mg/l, or ppm. A scale for the classification of particles of sediment by size is proposed by Helfgott, Hunter and Rickert (4):

Size Classification of Sediment Particles

	Particle Size	Description
1.	1 millimicron	Soluble particle
2.	10 millimicrons	Subcolloidal particle
3.	100 millimicrons	Colloidal particle
4.	1 micron	Colloidal particle
5.	10 microns	Supracolloidal particle
6.	100 microns	Suspended particle
7.	1 mm	Floc particle
8.	1 cm	Pebble
9.	1 dm	Rock
10.	1 m	Boulder

2. Biological Constituents

Included under this type are viruses, not classified as living organisms; bacteria and other primitive organisms claimed by botanists and zoologists; plants; and animals. They comprise the entire aquatic food chain. Certain water-borne viruses and bacteria may produce communicable diseases. It is impractical to measure concentrations of pathogenic organisms. So, it is assumed that pathogens coexist with high concentrations of fecal coliforms. -- They are measured in numbers per 100 milliliters (100 ml).

The symbiotic mode of living of bacteria with algae has been pointed out above. Together, they form phytoplankton, without which

protozoa cannot live. Most waters are deficient in phytoplankton, thus undernourished. Adequately nourished water resources are called eutrophic; overnourished ones, hypertrophic. Phreatophytes are water thieves.

Among animals, protozoa and micro-invertebrates form zooplankton. Macro-invertebrates, including shellfish and other mollusks, often are attached to the benthos. Vertebrates comprise fish, reptiles, and other aquatic animals.

3. Chemical Constituents (Dissolved Solids and Gases)

Many minerals and gases are water-soluble. The salts of many metals easily dissolve in water. Saturation points vary with temperature. Boiling and melting points of water vary somewhat depending on dissolved solid concentrations. Water can dissolve a number of solids simultaneously. The concentration of individual as well as total dissolved solids (TDS) is conveyed in milligrams per liter (mg/1), or more commonly in parts per million (ppm).

Dissolved chlorides, carbonates and silicates of sodium, potassium, calcium, and magnesium are essential for growth and reproduction of aquatic organisms. Not enough is known about human needs for minerals in drinking water. Distilled water is not the ideal quality. Approximately 200 ppm of TDS comes closer. In the U. S., 420 cities and

towns of over 1000 population were listed by Patterson and Banker (10) as using water containing 1000 ppm of TDS or more. Some communities use water with over 3000 ppm. Health authorities advocate no more than 500 ppm. The American Water Works Association upholds a goal of 200 ppm of TDS.

A rough measure of TDS concentrations is the degree of electric conductivity (also called specific conductance), in a water sample at 25° C. Such measurements do not replace TDS counts expressed in mg/1, ppm. or epm. "Equivalents per million" (epm) is a unit of measurement based on numbers of ions. All ions are chemically equivalent, and cation equivalents should very nearly balance anion equivalents. Nonionized solutes are not included in the count, which may therefore omit essential constituents only measurable in ppm. TDS are generally calculated. All ions are included, as well as elements (iron, silica, boron). Computed TDS may be slightly lower than the residue on evaporation.

Common salt combinations in fresh water include chlorides, fluorides and sulfates; prevalent metals are calcium, magnesium, iron, manganese, sodium and potassium. Dissolved oxygen and carbon dioxide are the principal gases. It is difficult to simplify the notation required to account for all the possible combinations of element in solution. One system extensively used by the U. S. Geological Survey

is the Triangular Water Analysis Diagram. It is shown in Figure 1. It consists of a vertical diamond wedged between two equilateral triangles forming the base. Cations (calcium, magnesium, and the sum of sodium plus potassium) are recorded in the left triangle. Anions (chloride, sulfate, and the sum of carbonate plus bicarbonate) are entered in the right triangle. Ions, in percent of half the total epm, are plotted as points in the triangles, then projected parallel to the diamond's upper sides, the intersections representing the character of the water.

Additional characteristics of water composition include: pH (potential of hydrogen), which indicates acidity (1-7), neutrality (7), or alkalinity (7-15). Hardness, as measured by compounds of calcium and magnesium, or more commonly by calcium carbonate ($Ca\ CO_3$) only, equals approximately the amount of hardness removed from boiled water. Hardness has been classified by the USGS as follows:

Hardness Range (calcium carbonate in ppm)	Description
0 - 60	Soft
61 - 120	Moderately hard
121 - 180	Hard
Over 180	Very hard

4. Color, Odor, and Taste

Color in water is measured in Jackson Color Units (JCU), and can usually be removed from domestic supplies at low cost. Turbidity

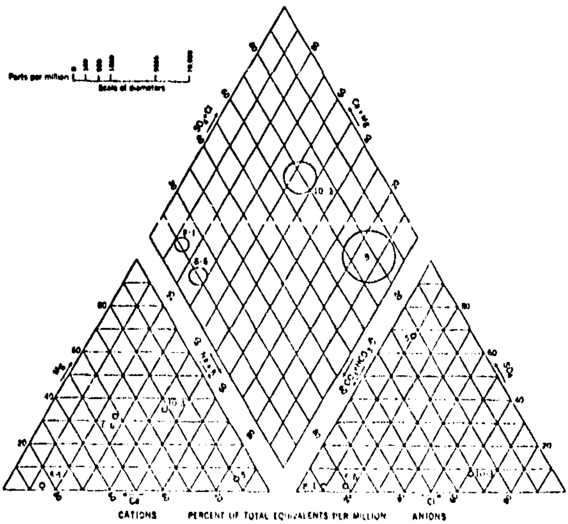

Figure 1 -Analyses represented by three points plotted in trilinear diagram (after A. M. Piper).

should not be a problem. It is measured by means of the Secchi Disk, a device used to measure visibility depth in water. The surface of a circular metal plate, 20 cm in diameter, consists of two opposite quadrants painted white with intervening quadrants painted black. The depth of disappearance measures turbidity.

Water absorbs light differentially. A layer of distilled water 1 meter thick absorbs 53% of solar radiation. The absorption ranges from 5% for 4500 angstrom to 90% for 7500 angstrom. Natural water absorbs far more light. In many large streams, the 25% level of solar radiation required for photosynthesis in green aquatic plants is not reached.

Odor may be caused by many substances of algal or other organic origin. Anaerobic conditions may generate hydrogen sulfide and other acrid dissolved gases. Industrial wastes may contain pungent substances.

Some of the same substances produce taste in water. In addition, dissolved organic salts may be detected by taste.

5. Toxic Constituents

Toxic substances and compounds, already covered under physical, biological or chemical constituents, deserve special mention because of the threat they present to life and growth. The frequency, variety,

volume, and concentration of toxic constituents of industrial origin exceed those of all other sources. Among them are metals, cyanides, detergents, sulfonates, herbicides, pesticides, arsenicals, carbamates, and acutely toxic chlorinated hydrocarbons and organic phosphorus.

6. Thermal Contamination

Standards for heated effluents are expressed in temperature differentials rather than in absolute temperatures. Permissible differentials may be 1°, 3°, or 5° F, so low that the heavy metals industry, for example is forced to use cooling towers.

7. Radioactive Contamination

Pure water cannot be radioactive, unless tritium, a hydrogen isotope, is present. But suspended and dissolved solids subjected to radiation and discharged into a water body can contaminate the phytoplankton and through it the entire food chain. The effects of radioactivity on all living organisms is cumulative. The prolonged exposure to unsuspected moderate radiation can cause health impairments difficult to diagnose and impossible to cure. -- Radioactivity is measured in picocuries per liter (pc/l). The picocurie is one millionth of a millionth of a curie.

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CHAPTER II. WATER QUALITY INDICES AND STANDARDS

In this chapter are discussed classifications and indices of water quality; water uses; effects and damages of water contamination; water quality requirements and standards.

A. Water Quality Classifications and Indices

Most types of water contaminants are represented in most water resources. The changing mixes of variable concentrations of a multitude of parameters of various types account for the phenomenal diversity of waters with regard to their aggregate, resultant quality. This makes attempts at classifying water quality, which varies in time and space, particularly complex.

1. Water Quality Classifications

Water quality can be classified by at least three criteria; by contaminants, by uses, and by treatment processes involved in removing contaminants.

Water quality classification by contaminants begins with a grouping of like characteristics into types such as those proposed in Chapter I, Section C. Under each of the seven types, individual parameters are listed, and the concentration of each parameter noted. To make measurements even more complex, possible chemical reactions among the many contaminants should be noted. Variations in time and space supplement the classification by parameters.

This makes the full identification and description of the quality of a particular water sample rather unwieldy. Yet, it is essential that all relevant water quality parameters be considered. It would not be safe to average parameters, or measure water quality by types only. A single parameter, such as viruses, arsenic, DDT, etc. can be critical. For these reasons, other avenues toward possible simplifications and shortcuts have been investigated.

Water quality classification by uses is an attempt to eliminate irrelevant water quality parameters. A requisite is that tolerances to each parameter, in terms of concentrations, be known or that safe water quality standards be available for each use. By means of tolerances or standards, one may discriminate, for each use, between critical and non-critical parameters. For example, high mineral content of water is critical in its use as domestic water supply; but in a recreational use such as swimming, even sea water is tolerated. By removing parameters which, for a given water use, are non-critical, the classification of water quality may be simplified while becoming more meaningful.

Another simplification is afforded by measuring water quality by the cost of bringing it to levels acceptable in given water uses. This presupposes that, in addition to tolerances or standards in various water uses, the effects of water treatment, in percent removal

of critical parameters, and the cost of such treatment, be known. Most water treatment processes are capable of removing more than one parameter, although possibly not by the same percent. By cumulating appropriate treatment processes, water quality can always be raised to any desired level.

Parameters that are critical in a given water use and yield to a given treatment can be combined into groups, thus simplifying considerably the classification of water quality. There exist but a limited number of water treatment processes, perhaps twenty in all; their combinations increase the number of possible treatment plant configurations. But if water quality is to be classified by treatment cost, the cost of all required processes is simply aggregated into a single figure. Waters of every description can thus be classified; and waters of widely differing quality, compared. -- The aggregate treatment cost can be used as a water quality index for a given water use.

2. Water Quality Indices

The need for judging over-all water quality in terms of individual parameters, particularly critical parameters, has been emphasized. One type of quality index, the cost of bringing water quality to desirable levels in given uses, has been described. Other water quality indices have been proposed in the literature. Each may serve a limited purpose. None is ideal.

Ernst & Ernst (1), in a report sponsored by the Corps of Engineers' Institute for Water Resources, investigated how water quality factors can be incorporated into water supply analysis. The authors made use of the cost of water treatment in relation to specific uses with known tolerances, without however utilizing that method for developing a water quality index.

Of the three water quality indices discussed in that report, the best appears to be Syracuse University's (3) Pollution Index (PI) comprised of 14 monitored water quality factors. They are: temperature, color, turbidity, bacteria, total solids, suspended solids, total nitrate, alkalinity, hardness, chloride, iron, manganese, sulfate, and DO.

For each factor, the measured value is divided by the recommended ceiling for each use, the resulting ratio for each factor and each use indicating the need for treatment if the value exceeds one. For each use, the mean impairment of the 14 factors is computed, but the maximum impairment is to be used along with the average. The pollution index is obtained by taking the square root of one-half the sum of the square of the mean impairment and the square of the maximum impairment.

The restricted number of quality parameters included in the index is its chief weakness, but the statistical technique is applicable to any desired number of quality factors. Time-variation should be added.

Other water quality indices described in the Ernst & Ernst report are that developed by the MITRE Corporation (2), called Prevalence-Duration-Intensity (PDI) Index, and that of Brown et al (4) of the National Sanitation Foundation. Both are based on subjective judgments and have other flaws.

One other water quality index is that developed by Dinius (5). Eleven water quality parameters are measured, subjected to a conversion factor to make all measurements comparable, and weighted before summation. The total, divided by 21, the sum of the weights, is the index. For comparability, all parameters are expressed in percents of "perfect water," 100% representing, for each parameter, zero concentration.

Weaknesses of this index are many:

(1) The number of parameters is inadequate.
(2) For each parameter, the concentration level identified with zero percent purity is arbitrary.
(3) The highest concentrations are clouded in the average.
(4) The weighting factors are constant for all water uses.
(5) User tolerances are ignored.

Sea water, for example, would receive the same index whether used for drinking or swimming; a highly toxic parameter might escape detection.

This points to the need for complete water quality analyses, and a matching of individual parameter concentrations with tolerances to each parameter in each water use. Any attempt at simplifying, combining, or averaging water quality parameters, or at judging water quality independently of its intended use, is fraught with hazards. It is not

the average link, but the weakest, that measures the strength of the chain. Likewise, it is the most critical parameter that measures the highest value of water in a given use.

3. Water Quality Data Collection

Water quality data are being collected by the federal-state network for water quality surveillance. EPA's storage and retrieval system (STORET) receives data from 24,000 stations. U. S. Geological Survey water quality monitoring stations feed into STORET data covering 31 parameters. They are:

*Temperature	*Hardness
*Specific conductance	*Radiochemical
*Turbidity	*DO
*Color	Other gases
*Odor	Minor elements
*pH (in the field)	Pesticides
*pH (in the laboratory)	Detergents
EH	*BOD
Suspended solids	Carbon (total, dissolved)
Other physical analyses	*Coliforms
*TDS	Other microorganisms
*Chloride	Biologic
*Nutrients (nitrogen)	*Sediment (suspended)
*Nutrients (phosphorus)	Particle size (suspended)
*Common ions	Particle size (bed load)
	Other sediment

* Parameters being monitored at over 1000 stations.

The U. S. Geological Survey has developed a system for improving accessibility to a broad spectrum of water data not restricted to water quality. It is called the National Water Data Exchange (NAWDEX).

B. Water Uses, and Effects of Water Contamination

In this section are listed the principal beneficial uses to which a water resource can be put. Also discussed here are effects on, and damages to, water users from water of impaired quality.

1. Water Uses

Principal water uses are enumerated here. Among water quality problems that are best analyzed with reference to water users and water use are: effects and damages of using water of impaired quality; establishment of users' tolerances to specific contaminants, and of water quality requirements and standards; determination of costs and benefits of upgrading water quality. These problems, with which water resource planners must wrestle, are discussed in the remaining pages of this report.

LIST OF WATER USES

(Irrigation, navigation, hydroelectric power, flood and drought control are omitted)

1. Municipal or Public Water Supply

   Residential or domestic use
   Commercial use
   Industrial use (of public supply)
   Institutional use
   Firefighting use

2. Private Industrial Water Supply

Boiler make-up use
Processing use
Product use
Cooling use
Sanitary use
Firefighting use

3. Recreational Water Uses

Water-contact activities

Swimming
Surf riding
Water skiing
Scuba-diving

Water-based activities

Fishing
Canoeing
Boating
Sailing

Water-related activities

Picknicking
Sunbathing
Camping
Hiking
Bicycling
Driving
Horseback riding
Hunting

Use of park facilities

Swimming pool use
Use of potable water for drinking, cooking, and flushing

4. Plant and Animal Habitat

Viruses and undifferentiated organisms

Plants

Bacteria, algae, phytoplankton
Water plants and other flora

Animals

Protozoa, microinvertebrates, zooplankton
Macroinvertebrates: insects, shellfish, other mollusks
Fish, Reptiles, Amphibians
Waterfowl
Other aquatic animal life
Wildlife seeking sanctuary, drinking water and food

5. Waste-Assimilative Capability

BOD and COD digestion
Sediment conveyance
Mineral dilution
Dilution of toxic materials
Dissipation of thermal inputs
Conveyance of radioactive substances

6. General Well-Being and Aesthetic Enjoyment

Well-being derived from the use of safe potable water, clean recreation water, and uncontaminated shellfish, fish, fowl, and meat

Well-being associated with fresh air breathing on or near large, clean, odorless water expanses

Well-being provided by communing with nature in the solitude of wild, unspoiled rivers, and the altitude of crystal-clear mountain lakes and streams

Aesthetic enjoyment obtained from beholding the natural beauty of pure rivers, streams, lakes, and ponds, in a setting of meadows, trees, forests, hills and mountains

7. Regional Economic Growth

Exploitation of water resources for attracting populations
Water resource and land development for residential and touristic purposes
Exploitation of water resources for attracting industry
Use of waste-assimilative capability of water resources

2. Effects and Damages of Water Quality Impairment, by Uses

Residential customers using a public water supply of substandard quality are subject to health impairment and to reduced life of plumbing and water appliances in the home.

The causes and incidence of waterborne diseases were reviewed by Craun and McCabe (6). From 1961 to 1970, there occurred in the U. S. 128 known outbreaks of disease or poisoning attributed to drinking water, with 46,374 illnesses and 20 deaths. Not included were cases of methemoglobinemia, the often fatal infant disease related to nitrate content in drinking water. Bean (7) presented a strong case for more research into this nitrogen hazard. A unified approach toward control of waterborne viruses was advocated by ASCE's Committee on Environmental Quality Management (8). Rice (9) made a valuable contribution by developing a method for measuring the cost of illness.

Damage done to water appliances in the home through use of water of inferior quality was assessed by Patterson and Banker (10). The authors surveyed 38 communities in 11 midwestern states with water supplies containing from about 100 to over 5000 ppm of TDS. For each

community, they obtained data on the average lives and maintenance costs of water facilities, including piping, heaters, faucets, toilet flushing mechanisms, garbage grinders, washing equipment, etc. The average life of each facility was plotted on a series of graphs against total dissolved solids, then read off the curves for two levels of TDS, 250 ppm and 1750 ppm. The differential in the estimated life corresponds to 1500 ppm spread in mineral content. Annual capital costs were computed for the two levels from replacement cost data, the difference for each facility representing the differential cost of the residential customer of having to replace the facility with a different frequency.

In addition, annual operation and maintenance costs were estimated for each facility, at the two levels of mineral content in the water, the difference indicating the incremental cost incurred annually by the same customer. When the two costs were aggregated, the total annual incremental cost amounted to $72.35.

Because modern urban residential customers own more water appliances and utilize 30% more water than the average residential customer, their total incremental annual water costs rose to $119.00. When the cost of bottled water use and of lawn sprinkling incurred by a certain proportion of customers is included, the totals rise to $184.35 for the average residential customer, and $239.00 for the modern urban residential customer.

The above estimates are reported in some detail because they are the most complete costs representative of the use of water of high mineral

content. They can be used in estimating the benefits of upgrading the mineral quality of water, and perhaps in setting standards of mineral water quality.

When considering the effects of water quality impairment on public water supply, it is relevant to assess also the impairment of municipal water quality as a result of its utilization, and the damages of such impairment to future users. This is of particular interest when recycling of the water supply is contemplated for internal reuse. Persistent contaminants are not removed by customary sewage treatment processes. Helfgott et al (11) have listed incremental increases in inorganic and organic content due to a once-through utilization of public water supply:

Analysis of Inorganics and Gross Measures of Organics Added to a Public Water Supply Through its Utilization

Parameter	Average Increment per Use (mg/1)
Inorganics	
Cations	
Na^+	16
K^+	10
NH^+	15
Ca^{++}	18
Mg^{++}	6
Anions	
Cl^-	74
NO_3^-	10
NO_2^-	1
HCO_3^-	100

CO_3^{--}	--
SO_4^{--}	28
SiO_3^{---}	15
PO_4 (Total)	24
PO_4^{---} (Ortho)	25
Others	
Hardness (as $CaCO_3$)	79
Alkalinity (as $CaCO_3$)	81
TDS	320
pH (in H ions)	0.6
Organics	
BOD	16
COD	87
MBAS*	6.4

Today's water treatment technology permits the utilization of surface water of literally any quality to produce industrial water acceptable in all six uses. The treatment may not be inexpensive; however, except for the seven largest water-using industries, its cost may be but a small fraction of value added.

Recreational water uses, especially water-contact sports, are subject to harmful consequences of water contamination. In addition to health impairments already discussed, swimmers may contract skin irritations, eye, ear, and nose infections. These may be traced to

*MBAS = Methylene blue active substances, formerly represented only by anionic detergents, but now extended to include chemically related materials.

microorganisms present above safe concentrations. Damages from polluted recreation waters may be measured by the cost of water-borne diseases and infections, but also by the loss of recreational water benefits when public safety dictates the prohibition of water use.

Fish caught in polluted water may have ingested harmful germs, toxic compounds, or radioactive substances. Shellfish are particularly subject to contamination by excrements of waterfowl and mammals, and by human sewage.

Use of park facilities is predicated on the availability of potable water. The damage of being denied access to a recreational facility is another costly effect of water pollution.

Plankton is essential to all aquatic life. Chlorine, herbicides, pesticides, toxic substances, and acid mine drainage, when in sufficient concentrations, may drastically reduce the population of microorganisms. This threatens the survival of the higher echelons of the food chain.

A measure of the damage caused to plant and animal life by impurities in the water is afforded by benthic macroinvertebrates. Many species are extremely sensitive to pollution. Quantitative sampling shows changes in dominance or abundance; qualitative sampling determines the variety of species. The Sequential Comparison Index (SCI) is advocated by Cairns and Dickson (12) as a simplified method for estimating relative differences in biological diversity. Specimens

poured into a pan with parallel lines drawn on the bottom are read in sequence. Each repetition is represented by a repetition of the letter X or O; each switch by a switch. The Diversity Index (DI) is the number of switches divided by the number of specimens. A low DI is indicative of critical water contamination.

Fishkills, now officially recorded, provide another measure of harmful water pollution. Tolerances of fish to thermal and other contamination are much more critical than those of macroinvertebrates.

The need for conveying partially treated sewage and industrial wastewater to the sea is so great that this is one of the most valuable services a stream can render to society. The waste-assimilative potential of a water resource, and its capacity to dilute dissolved solids, thermal discharges, toxic materials and radioactive substances has high economic value, and a loss of such capability represents an economic damage to its users.

Aesthetic enjoyment is affected by unsightly debris floating on the water, by turbulence, color, odor, acidity, excessive growth of algae and phreatophytes. Measurement of an impairment of aesthetic enjoyment will probably long remain subjective, resisting quantification and reduction to a monetary loss.

Regional economic growth, as well as land values, may be affected by water of inferior quality. Water of poor quality can be a deterrent to both tourism and industry.

C. Water Quality Requirements and Standards

Water quality requirements in various water uses are determined through experience and scientific investigations. Based on these, responsible authorities set up water quality criteria and standards applicable to the respective uses.

Requirements are not always clear-cut. No expense should be spared in making water safe for drinking. In other uses, the desirability of high water quality may be a matter of preference, or of comparative economic worth. Many quality requirements may properly be expressed as ranges rather than specific levels. Some assistance in determining desirable degrees of water purity in given uses is lent by economics: marginal benefits and marginal costs should be equated by a water quality improvement project. But costs and benefits vary with the original water quality and with numbers of water users. In the absence of a particular project, water quality requirements can best be determined on the basis of a more general yardstick of the value of water quality in specified uses.

In the curve of utility of water quality to a class of users, a threshold often occurs beyond which costs make a quantum jump or benefits drop close to zero. The need for reducing TDS by only 100 ppm may translate into adding a prohibitively expensive desalination process. A temperature differential of 2 or 3 degrees may make the difference

between life and death of some fish species. Many water quality requirements have been based on such considerations.

Official policy-making agencies promulgate water quality criteria and standards taking into account recognized water quality requirements of water users. Private groups advocate water quality goals. When benefits are difficult to estimate and costs are incompletely known, water quality criteria, standards and goals prove helpful as guides in making reasonable choices. And where water quality benefits, damages, and costs do not accrue to identical water users, uniform water quality criteria and standards permit an equitable resolution of externalities. -- Because of widely variable tolerances of different groups of water users, water quality criteria, standards, and goals are reviewed in the following paragraphs by water uses.

1. Public Water Supply

For public water supplies, six sources of water quality criteria, standards, and goals are available. The first in time was the U. S. Public Health Service's Drinking Water Standards of 1962 (13). The second source was the Water Quality Criteria by McKee and Wolf (14) of the California State Water Quality Control Board, 1963. The National Technical Advisory Committee (NTAC) published its Water

Quality Criteria (15) in 1968. This third source, known as the "Green Book," includes all principal water uses and is quoted extensively here and in subsequent subsections. Detailed data used in its preparation were published by EPA in 1970-72 in the four-volume Water Quality Criteria Data Book (19).

The fourth source was the series of Potable Water Quality Goals published in December 1968 by the American Water Works Association (16). International Standards for Drinking Water published in 1971 by the World Health Organization (17) was the fifth source. The sixth was EPA's Drinking Water Standards (20) dated September 1973.

These six sources were used in developing two comparative tables, the first for raw public water supply, the second for finished domestic water.

RAW WATER QUALITY CRITERIA

Parameter	Unit	McKee & Wolf 1963 Mand.	McKee & Wolf 1963 Desir.	NTAC 1968 (a) Mand.	NTAC 1968 (a) Desir.	WHO 1963
Physical Param.						
Color	PCU	150	20	75	10	300
Odor	TON	-	-	Narr.	V.abs.	Unobject.
Temperature	Degrees C	-	-	Narr.	Narr.	-
Turbidity	JTU	250	10	Narr.	V.abs.	-
Biological Param.						
Coliforms	No/100 ml	5000	100	10000(b)	100(b)	50000
Fecal coliforms	No/100ml	-	-	2000(b)	20(b)	-
Inorganic Chemicals						
Alkalinity ($CaCO_3$)	mg/l	-	-	Narr.	Narr.	-
Ammonia (as N)	mg/l	-	-	0.5	0.01	0.05
Arsenic	mg/l	-	-	0.05	Abs.	0.05
Barium	mg/l	-	-	1.0	Abs.	-
Boron	mg/l	-	-	1.0	Abs.	-
Cadmium	mg/l	-	-	0.01	Abs.	0.01
Chloride	mg/l	250	50	250	25	-
Chromium, hexav.	mg/l	-	-	0.05	Abs.	0.05
Copper	mg/l	-	-	1.0	V.abs.	1.5
Dissolved oxygen	mg/l	4-6.5	4-7.5	-	-	-
	% satur.	60%	75%	-	Near	-
monthly mean	mg/l	-	-	4+	-	-
indiv. sample	mg/l	-	-	3+	-	-
Fluoride	mg/l	3.0	1.5	Narr.	Narr.	1.5
Hardness	mg/l	-	-	Narr.	Narr.	-
Iron, filterable	mg/l	-	-	0.3	V.abs.	50
Lead	mg/l	-	-	0.05	Abs.	0.05
Manganese, filt.	mg/l	-	-	0.05	Abs.	-
Nitrates,nitrites	mg/l	-	-	10	V.abs.	10
pH range	H ions	5-9	6-8.5	6-8.5	Narr.	-
Phosphorus	mg/l	-	-	Narr.	Narr.	-
Selenium	mg/l	-	-	0.01	Abs.	0.01
Silver	mg/l	-	-	0.05	Abs.	-
Sulfate	mg/l	-	-	250	50	-
TDS, filt. residue	mg/l	-	-	500	200	1500
Uranyl ion	mg/l	-	-	5	Abs.	-
Zinc	mg/l	-	-	5	V.abs.	15

Parameter	Unit	McKee & Wolf 1963 Mand.	McKee & Wolf 1963 Desir.	NTAC 1968 (a) Mand.	NTAC 1968 (a) Desir.	WHO 1963
Organic Chemicals	mg/1					
BOD		4	3	-	-	6
CCE (c)		-	-	0.15	0.04	0.5
COD		-	-	-	-	10
Cyanide		-	-	0.20	Abs.	0.02
Herbicides		-	-	0.1	Abs.	-
MBAS (d)		-	-	0. 5	V.abs.	-
Oil & grease		-	-	V.abs.	Abs.	1
Pesticides						
Aldrin		-	-	0.017	Abs.	-
Chlordane		-	-	0.003	Abs.	-
DDT		-	-	0.042	Abs.	-
Dieldrin		-	-	0.017	Abs.	-
Endrin		-	-	0.001	Abs.	-
Heptachlor		-	-	0.018	Abs.	-
H. epoxide		-	-	0.018	Abs.	-
Lindane		-	-	0.056	Abs.	-
Methoxychlor		-	-	0.035	Abs.	-
Org.phosphates & carbamates		-	-	0.1	Abs.	-
Toxaphene		-	-	0.005	Abs.	-
Phenols		0.005	None	0.001	Abs.	0.002
Radioactivity (e)	pc/1					
Gross beta		-	-	1000	100	-
Radium 226		-	-	3	1	-
Strontium 90		-	-	10	2	-

Narr. = Narrative evaluation
Abs. = Absent
V.abs. = Virtually absent
Unobject.= Unobjectionable

(a) The nature and extent of the expected raw water treatment are defined in the "Green Book." Simple processes will produce drinking water of acceptable quality.

(b) Microbiological limits are monthly arithmetic averages based upon an adequate number of samples. Total coliform limit may be relaxed if fecal coliform concentration does not exceed the specified limit.

(c) CCE = Carbon-chloroform extract.

(d) MBAS = Methylene blue active substances.

(e) The unit for radioactivity is the picocurie, or micro-microcurie, per liter, expressed by pc/l.

TREATED WATER QUALITY STANDARDS AND GOALS

Parameter	Unit	PHS 1962 Mand. (a)	PHS 1962 Desir. (b)	AWWA 1968 (c)	WHO 1971 Mand. (d)	WHO 1971 Desir. (d)	EPA 1973 Health	EPA 1973 Esth.
Physical Param.								
Color	PCU	-	15	3	50	5	-	15
Non-filt.solids	mg/1	-	-	0.1	-	-	-	-
Odor	TON	-	-	None	Unobj.	Unobj.	-	3
Taste	-	-	-	Unobj.	Unobj.	Unobj.	-	-
Turbidity	JTU	-	1	0.1	25	5	1	-
Biological Param.								
Coliforms filter	No/100 ml	1 or 4 (e)	-	None	-	-	1 or 4 (e)	-
ferment	No/100 ml	-	-	None	-	-	-	-
Fecal coliforms	No/100 ml	-	-	None	-	-	-	-
Macroscopic organisms	No.	-	-	None	-	-	-	-
Inorganic Chemicals								
Alkalinity ($CaCO_3$)	mg/1	-	-	(f)	6.5-9.2	7.0-8.5	-	-
Aluminum	mg/1	-	-	0.05	-	-	-	-
Arsenic	mg/1	0.05	0.01 (g)	-	0.05	-	0.1	-
Barium	mg/1	1.0	-	-	-	-	1	-
Boron	mg/1	5.0(h)	1.0(h)	-	-	-	-	-
Cadmium	mg/1	0.01	-	-	0.01	-	0.010	-
Calcium	mg/1	-	-	-	200	75	-	-
Chloride	mg/1	-	250	-	600	200	-	250
Chromium, hexavalent	mg/1	0.05	-	-	-	-	0.05	-
Copper	mg/1	-	1.0	0.2	1.5	0.05	-	1
Corrosion	mg/sq cm	-	-	5.00 (i)	-	-	-	-
Fluoride	mg/1	(j)	(j)	-	(j)	(j)	(j)	-
Hardness	mg/1	-	-	80(k)	500	100	-	-
Incrustation	mg/sq cm	-	-	0.05(l)	-	-	-	-
Iron, filter	mg/1	-	0.3	0.05	1.0	0.1	-	0.3

Parameter	Unit	PHS 1962 Mand. (a)	PHS 1962 Desir. (b)	AWWA 1968 (c)	WHO 1971 Mand. (d)	WHO 1971 Desir. (d)	EPA 1973 Health	EPA 1973 Esth.
Lead	mg/l	0.05	-	-	0.1	-	0.05	-
Magnesium	mg/l	-	-	-	150	30-150(m)	-	-
Manganese, filterable	mg/l	-	0.05	0.01	0.5	0.05	-	0.05
Mercury	mg/l	-	-	-	0.001	-	0.002	-
Nitrates & Nitrites(N)	mg/l	-	45	-	45	-	10	-
Selenium	mg/l	0.01	-	-	0.01	-	0.01	-
Silver	mg/l	0.05	-	-	-	-	0.05	-
Sulfate	mg/l	-	250	-	400	200	-	250
TDS, filt. residue	mg/l	-	500	200	1500	500	-	-
Zinc	mg/l	-	5	1.0	15	5	-	5
Organic Chemicals	mg/l							
CAE		-	-	-	-	-	3.0	-
CCE		-	0.2	-	0.5	0.2	0.7	-
Cyanide		0.2	0.01	-	0.05	-	0.2	-
Herbicides								
2, 4-D		-	-	-	-	-	0.02	-
2,4,5-TP(Silvex)		-	-	-	-	-	0.03	-
MBAS		-	0.5	-	1.0	0.2	-	0.5
Mineral Oil		-	-	-	0.30	0.01	-	-
Pesticides		-	-	-	-	-		-
Aldrin							0.001	
Chlordane							0.003	
DDT							0.05	
Dieldrin							0.001	
Endrin							0.0005	
Heptachlor epoxide							0.0001	
Lindane							0.005	
Methoxychlor							0.1	
Org. phosphates and carbamates (parathion)							0.1	
Toxaphene							0.005	
Phenols		-	-	-	0.002	0.001	See odor	-
Radioactivity (n)	pc/l							
Gross alpha		-	-	-	3/10(o)	-	-	-
Gross beta		1000(p)	-	100	30/1000(q)	-	-	-
Radium 226		-	3	-	-	-	-	-
Strontium 90		-	10	-	-	-	-	-

Unobj. = Unobjectionable

(a) If the concentrations of any of these constituents are exceeded, the further use of this water for drinking and culinary purposes should be evaluated by the appropriate health authority because water of this quality represents a hazard to the health of consumers.

(b) If the concentration of any of these constituents is exceeded, a more suitable supply or treatment should be sought.

(c) For all health-related constituents not stated herein, these goals shall require complete compliance with all recommended and mandatory limits contained in current USPHS Drinking Water Standards. Unless other methods are indicated, analyses shall be made in conformance with the latest edition of Standard Methods for the Examination of Water and Wastewater.

(d) Mandatory limits are called "allowable"; desired limits, "acceptable".

(e) Water quality fails the standard if:
 (1) arithmetic average of samples collected is greater than 1 per 100 ml; or
 (2) two or more samples (5% or more if more than 20 are examined) contain densities more than 4/100 ml.

(f) Alkalinity should not change by more than 1 mg/1 (decrease or increase in distribution system, or after 12 hours at 130°F. in a closed plastic bottle, followed by filtration).

(g) Although the recommended arsenic concentration is 0.01 mg/1, because of interferences in some waters, the concentration of arsenic was only determined to be less than 0.03 mg/1. For the purposes of this study, these waters were considered not to exceed the recommended standard.

(h) Proposed for inclusion in the Drinking Water Standards.

(i) Loss by corrosion of galvanized iron by coupon tests.

(j) Public Health Service limits are as follows: Temperatures shown for fluoride concentrations are annual average maximum day temperatures for 5 years or more.

Temperature	Limits (mg/l) Mandatory	Desirable
50.0 - 53/7° F	2.4	1.7
53.8 - 58.3° F	2.2	1.5
58.4 - 63.8° F	2.0	1.3
63.9 - 70.6° F	1.8	1.2
70.7 - 79.2° F	1.6	1.0
79.3 - 90.5° F	1.4	0.8

The World Health Organization recommends the following upper and lower control limits which should be considered mandatory:

Annual average of maximum daily air temperatures	Limits (mg/d) Lower	Upper
10 - 12° C	0.9	1.7
12.1 - 14.6° C	0.8	1.5
14.7 - 17.6° C	0.8	1.3
17.7 - 21.4° C	0.7	1.2
21.5 - 26.2° C	0.7	1.0
26.3 - 32.6° C	0.6	0.8

EPA's limits are, for temperatures of 65° F or less, 1.5 mg/l; 66 - 79° F, 1.3 mg/l; 80° F or over, 1.2 mg/l.

(k) A balance between deposition and corrosion characteristics is necessary; a level of 80 mg/l seems best, generally, considering all the quality factors; however, for some supplies, a goal of 90 or 100 mg/l may be deemed desirable.

(l) By 90-day coupon tests on stainless steel.

(m) If 250 mg/l of sulfate are present, not more than 30 mg/l of magnesium are desirable; with less sulfate, magnesium up to 150 mg/l may be allowed.

(n) The unit for radioactivity is the pico-curie or micro-micro-curie per liter, expressed by pc/l.

(o) If radium 226 activity exceeds 3 pc/l, 3 pc/l of alpha radiation is the mandatory limit; if radium 226 activity is below 3 pc/l, 10 pc/l of alpha radiation are permissible.

(p) Acceptable in water in the known absence of strontium 90 and alpha emitters.

(q) If strontium 90 activity exceeds 30 pc/1, 30 pc/1 of beta radiation is the mandatory limit; if strontium 90 activity is below 30 pc/1, 100 pc/1 of beta radiation are permissible; and if strontium 90 activity is below 30 pc/1 and iodine 129 activity is below 100 pc/1, then 1000 pc/1 of beta radiation are permissible.

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2. Private Industrial Water Supply

Industrial water quality needs vary greatly, first with the six functions of water in industry, second with the industry. The functions are:

Boiler make-up
Processing water
Product water
Cooling water
Sanitary water
Firefighting water

Boiler make-up water quality must meet very specific requirements. These are not listed here, inasmuch as some desalting process is usually required and quantities of make-up are small. A table of tolerances is available on page 194 of the "Green Book".

Processing water quality requirements are spelled out in the "Green Book" for the following industries:

Textile mill products
Lumber and wood products
Paper and allied products
Chemical and allied products
Petroleum and coal products
Primary metal industries
Food canning industry
Soft drinks industry
Tanning industry
Cement industry

A more detailed list of 37 industries and their water quality tolerances appeared in the Report of the U. S. Study Commission -- Texas (March 1962), and was reprinted in the March 1970 issue of the American Water Works Association Journal, pages 150-151.

Cooling water quality requirements can be summed up in a few words. It should be non-corrosive, non-erosive, non-scaling, and should prevent sludge accumulation and the growth of slime-forming microorganisms. To achieve these simple goals, a long list of water quality requirements is detailed in the "Green Book". Since cooling water is used in large quantities in many industries including power plants, the table is reproduced below:

Industrial Cooling Water Standards
(in mg/l)

Characteristic	Fresh Water Once thru	Fresh Water Make-up	Brackish Water Once thru	Brackish Water Make-up
Silica (SiO_2)	50	50	25	25
Aluminum	(a)	0.1	(a)	0.1
Iron	(a)	0.5	(a)	0.5
Manganese	(a)	0.5	(a)	0.02
Calcium	200	50	420	420
Magnesium	(a)	(a)	(a)	(a)
Ammonia (NH_4)	(a)	(a)	(a)	(a)
Bicarbonate (HCO_3)	600	24	140	140
Sulfate (SO_4)	680	200	2,700	2,700
Chloride	600	500	19,000	19,000
Dissolved solids	1,000	500	35,000	35,000
Copper	(a)	(a)	(a)	(a)
Zinc	(a)	(a)	(a)	(a)
Hardness ($CaCO_3$)	850	130	6,250	6,250
Free mineral acidity ($CaCO_3$)	(b)	(b)	(b)	(b)
Alkalinity ($CaCO_3$)	500	20	115	115
pH (H ions)	5-8.3	(a)	6-8.3	(a)
Color (PCU)	(a)	(a)	(a)	(a)
MBAS	(a)	1	(a)	1
Carbon tetrachloride extract	(c)	1	(c)	2
COD (O_2)	75	75	75	75
DO (O_2)	(a)	(a)	(a)	(a)
Temperature (F)	(a)	(a)	(a)	(a)
Suspended solids	5,000	100	2,500	100

(a) Accepted as received (if meeting total solids or other limiting values); has never been a problem at concentration levels encountered.

(b) Zero, not detectable by test.

(c) No floating oil.

Source: Water Quality Criteria, Report of the National Technical Advisory Committee to the Secretary of the Interior, FWPCA, April 1968.

3. Recreational Water

Quality requirements for water-contact recreation can be summed up in this Public Health Service recommendation: "The fecal coliform content should not exceed a log mean of 200/100 ml, nor should more than 10% of total samples during any 30-day period exceed 400/100 ml; in addition, to avoid excessive eye irritation, the pH should be within the range of 6.5 to 8.3, in no case less than 5.0 or more than 9.0."

For other recreational uses, the fecal coliform content should not exceed a log mean of 1000/100 ml, nor 2000/100 ml in more than 10% of the samples. For the enjoyment of recreation, water quality should also be adequate for the support of flora and fauna. For the protection of fishermen and hunters, fish, shellfish, waterfowl and game should be fit for human consumption.

Quantitative recreational water requirements may conflict with those of public water supply and other uses when a reservoir is involved. Residential water demand may be at its peak in the summer months because of lawn sprinkling. In addition, if drought control and quality storage are among the purposes of the reservoir, the release of water when flow is at a low point is essential. On the other hand, flood control demands at all times extra capacity in the reservoir. How,

then, can the needs of recreation be protected? This is a perennial management problem for reservoir operators. Sometimes, pumped storage operated in conjunction with gravity storage can alleviate the difficulty.

4. Plant and Animal Habitat

Aquatic plant and animal species are so numerous and their individual tolerances to water contaminants so diverse that their water quality needs are extremely complex. The knowledge we possess, albeit incomplete, encompasses 84 two-column pages and 243 references in the "Green Book." Tolerances are arranged by water quality parameters under three main headings: fresh water organisms, marine and estuarine organisms, and wildlife.

A few general recommendations are summarized here: Dissolved materials should not be increased by more than one-third of the natural water concentration. No highly dissociated materials should be added in quantities sufficient to lower the pH below 6.0 or to raise it above 9.0. Temperatures, which are critical to many fish species, should not be increased so as to raise the monthly average of maximum daily levels by more than 5° F in streams, or 3° F in lakes and reservoirs. DO concentrations are critical to many species. Ten percent of the incident light must reach the bottom of any desired photosynthetic zone in which adequate DO levels are to be maintained.

To preserve suitable waterfowl food plants, salinity fluctuations in a 24-hour period should not exceed 1,000 ppm in fresh water, 2,000 ppm in moderately brackish water (3,500 - 13,500 ppm), or 4,000 ppm in strongly brackish water. The habitat should be free of oil.

5. Waste Assimilation

The law no longer permits the use of water resources as waste carriers, diluters, or purifiers. Economically, it is not always possible to show that the benefits of clean water to society exceed the value of waste removal opportunities foregone by public and private water utilities. The waste-assimilative capability of each water resource is limited by its self-purification rate and quality needs for other water uses. The requirements placed on water quality for waste assimilation are not recognized in the "Green Book".

In a study of stream assimilative capacity, Busch (18) contended that the maximum waste-assimilative capacity of a stream equals its minimum reaeration capacity. The significant waste-assimilative capacity of a stream is that which does not lower the oxygen content below a predetermined value. This is the maximum capacity which should be made available for intentional waste assimilation. Oxygen should not be used faster than it is transferred into the water by natural phenomena or artificial instream aeration. Hence, the assimilative

capacity of a water body is determined by the product of the minimum oxygen transfer coefficient, the maximum permissible DO deficit, and the surface area being considered.

6. Aesthetic Enjoyment and General Well-Being

Surface waters should be capable of supporting life forms of aesthetic value. They should be free of wastes that settle to form objectionable deposits; free of debris, oil and scum; free of substances producing objectionable color, odor, or taste; free of toxic materials and radionuclides; and free of nutrients which produce undesirable aquatic life.

7. Regional Water Quality Needs

Economic growth is promoted by clean water. Populations flock to it. Water should be available in sufficient quantities and suitable quality for a variety of industrial uses. The most favored areas will always be sought out by the seven largest water-using industries. But there exist a substantial group of industries which require comparatively little water, the quality of which either is not critical or can be upgraded at a cost representing a negligible fraction of value added.

Man can do a great deal to assist nature in the enhancement of land values. Greenbelts developed along the course of streams of high water quality can provide parks for recreational purposes and add to the attractiveness of adjoining residential land.

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CHAPTER III. WATER QUALITY MODELS

A number of water quality models have been developed, with various objectives in mind. In many cases, the purpose is to permit planners to observe on paper the probable effects of alternate water quality allocation or enhancement measures.

A. Generalities

Some of the models are labeled simulation models, others predictive models, stochastic models, or real time models; some are used for sensitivity analysis; and many have been subjected to empirical verification. Some models are applicable primarily to streams, others to estuaries, others again to lakes and reservoirs.

The greatest diversity exists among the water quality constituents modeled. Sophisticated models have been created on the basis of a single water quality parameter, e.g., BOD. At the other extreme are found models incorporating a number of meteorological, hydrological, physical, biological, chemical (inorganic, organic, toxic, and radio-active) parameters; models that simulate natural phenomena: digestive efficiency, respiration, algal growth, photosynthesis, BOD decay, stratification; and artificial events: flow augmentation, aeration, time-varying waste discharges, thermal pollution, and many more.

An ideal model has not yet been fashioned. It should encompass a large number of water quality parameters, simulate dynamic changes in a large number of variables, predict long-run effects of alternate measures, and solve optimally a number of water quality management problems. The stochastic nature of water quality should be taken into account, and costs, damages, and benefits, represented in the model.

United States water quality monitoring stations collect only a limited amount of information. The Geological Survey covers 31 parameters, 18 of which are collected from over 1000 stations. Practicality dictates selectivity. But every time a simplified list of water quality parameters is proposed, dire omissions can easily be detected. In his critical review of water quality models, Lombardo (20) recommends the inclusion of 14 parameters: Alkalinity, ammonia, BOD, chlorophyll a, DO, fecal coliforms, fecal streptococci, nitrate, phosphate, pH, temperature, TDS, turbidity, and zooplankton. It is immediately apparent that sediment, hardness, heavy metals, herbicides, pesticides, other toxic as well as radioactive substances, any of which may be critical in some uses, are simply lacking.

Other desirable capabilities of water quality models, as listed by Lombardo, include: Time- and space-variable simulation, responsiveness to hydrologic influences, surface runoff quality simulation,

varying time-interval simulation, amenability to graphical output, reasonableness of operating cost.

Several excellent reviews of water quality models are available to the planner. Harper (16) assessed mathematical models simulating DO and BOD in streams and estuaries. Roesner (27) reviewed models of heat transfer through the air-water interface of a flowing stream. Orlob (26) and Ward and Espey (33) evaluated mathematical modeling techniques applied to estuarine systems. Lombardo's (20) critique covers six of the more comprehensive and flexible odels. These, plus the more recent model by Waddell et al (32) are analyzed below in greater detail.

The Environmental Protection Agency is sponsoring a series of projects in its various regions for modeling three conservative and eight nonconservative constituents. Most of them are aimed at adding quality simulation capability to one or more of six existing models:

Model	Developer	Reference
QUAL-1	Texas Water Development Board	30
DOSAG-1	Texas Water Development Board	29
Deep Reservoir Model	Water Resources Engineers, Inc.	34
Receiving Water Module of Storm Water Management Model	Metcalf & Eddy et al	23

Dynamic Estuary Model (DEM)	Feigner & Harris (EPA)	10
Mathematical Model of Columbia River	Callaway & Bysam (EPA)	3

B. Model Reviews

Eight models are primarily concerned with the time-and space-variable dissolved oxygen balance in streams. They were developed by Thayer and Krutchkoff (31), O'Conner (24), O'Conner and Di Toro (25), Dixon and Hendricks (7), Goodman and Tucker (13), Frankel and Hansen (12), Weeter (35), and Loucks and Lynn (22). Three models specifically include canals with rivers: White and Tischler (36) were concerned with an assessment of waste-assimilative capacity; and the Texas Water Development Board (29 and 30) computed flow augmentation needed to raise DO to a target level, and predicted spatial and temporal quality variations on an hourly basis. Other river models are referred to in Chapters IV and VII. That by Bishop and Hendricks (2) deserves mention here because of its regional water balance concept, and its integrated quantitative and qualitative water supply allocation scheme which provides for cascading and renovated water reuse.

Estuaries are not included in this study. Several estuarine models have equal applicability to rivers. Among them are FWPCA's Delaware Estuary Comprehensive Study (9), Graves and Hatfield's (14) and Graves, Hatfield and Whinston's (15) models of the same estuary.

Statified layers of lakes and reservoirs have been modeled by Simons (28), Bella (1), Dingman and Johnson (5), and the EPA (8). Some used a three-dimensional universe to account for currents, temperature, and pollutants; the EPA model is one-dimensional, in the vertical direction only, and proved capable of predicting temperature changes in close agreement with actual measurements. Jaworski et al (18) used a model to determine optimal reservoir releases for water quality control.

Seven water quality models deserve closer scrutiny. Waddell et al (32) of Battelle's Pacific Northwest Laboratories integrated a number of partial models into a more complete system. Their dynamic and predictive model, called EXPLORE-I, is applicable to river basins, with provisions for including tributaries, estuaries, stratified lakes and impoundments. Sixteen water quality constituents were modeled: BOD (benthic, carbonaceous, and nitrogenous), carbon (refractory organic, and total organic (TOC)), DO, nitrogen (ammonia, nitrate, nitrite, and organic), phosphorus (organic, sedimentary, and soluble), phytoplankton, toxic compounds, and zooplankton.

Additional parameters recognized in the model are: algae, coliforms, heavy metals, pesticides, photosynthesis, reaeration, and respiration. Use or adaptations were made of existing models for seven categories of parameters: Algae, BOD, DO, N, P, TOC, and toxic compounds. The model for planktonic algae considers the effects on

growth of temperature, light intensity, and limiting nutrients such as nitrogen and phosphorus. The decrease of phytoplankton is due to natural respiration and zooplankton grazing. Zooplankton population is limited by respiration, the availability of phytoplankton, etc.

For BOD, a first-order carbonaceous model was selected. The nitrogenous oxygen demand is treated separately by the nitrogen model. The benthic demand is treated as a first-order material or a conservative mineral. It is coupled to the suspended and dissolved BOD model through sedimentation and scour terms, and to the DO equation through an exertion rate constant. The DO equation considers the following effects: Carbonaceous and nitrogenous BOD exertion, benthic oxygen demand, reaeration, and photosynthesis of phytoplankton and attached plants.

The nitrogen model describes the relationships between algal nitrogen, organic nitrogen, nitrate, nitrite, and ammonia nitrogen. The phosphorus model, not unlike the nitrogen model, simulates relationships between algal phosphorus, organic phosphorus, soluble, and sedimentary phosphorus. No model could be found to portray TOC. First order equations were developed to correlate TOC with BOD and COD. A general model was added to describe the changes in various compounds such as toxic substances, heavy metals, and coliforms.

Two submodels are required to account for water quality throughout a river basin: A hydraulic code features channels (one-dimensional flow) and junctions (two-dimensional flow). Junctions are storage elements for water and potential energy. A reservoir code, developed from a multi-segment reservoir model, provides for temperature and stratified flow.

The model was used to predict water quality changes in the Willamette River Basin between Salem and Portland, Oregon, and in the Detroit Reservoir located above Salem. Actual data conformed well to predictions.

Harper (17) developed a model applicable to a river system comprised of discrete "continuously stirred tank reactor" (CSTR) elements, with water flowing from one to the next. For each time interval, a multiple-step explicit solution was used to solve the partial differential equations describing the water quality processes. Travel time, dispersion, and mass generation were determined.

The model is capable of simulating the following parameters: Algae (benthic), BOD, carbon (total, carbon dioxide, pH system), conservative constituents, DO, nitrate nitrogen, phosphate (ortho, total inorganic), phytoplankton, and temperature.

It is apparent that Harper's coverage of water quality parameters falls far short of Waddell's. It also assumes steady-state hydrological conditions.

Di Toro et al (6) modeled water quality in rivers and estuaries. The authors developed a methodology for describing the population dynamics of phytoplankton and zooplankton. The conservation of mass is the underlying principle of the model. Phytoplankton dynamics are considered a function of: (1) growth, itself dependent on light, nutrients and temperature; (2) respiration, a linear function of temperature; (3) zooplankton grazing; and (4) sinking. Zooplankton is determined by (1) growth, itself governed by assimilation efficiency at high phytoplankton population; (2) respiration; (3) predation by higher trophic levels. Nutrients are a mass balance of plankton uptake and release.

The model was applied to the San Joaquin River in California, with good conformity of calculated to observed data for plankton and inorganic nitrogen.

Lombardo and Franz (21) constructed a mathematical model to simulate water quality dynamics in rivers and impoundments. It is linked to Hydrocomp's Hydrologic Simulation Program (HSP) which represents the hydrologic response of a watershed. Through use of both models, the hydrologic and water quality interactions of a water-

shed can be simulated. The HSP system, an outgrowth of the Stanford Watershed Model (SWM) of 1966, calculates, for each successive river reach progressing downstream, the inflow volume from rainfall, and loss through evapotranspiration; the flow at the end of the reach is calculated by the kinematic wave routing method. Point sources and diversions may be specified throughout the stream network. The contours and areas of vertical planes between successive reaches are noted. Lakes are assumed to consist of three layers.

At this point, quality data are introduced. Water quality changes in channel flows, as well as surface runoff quality, are simulated. Each river reach and each lake layer is assumed to be a CSTR, and a multiple-step explicit solution is used to solve the partial differential equations describing water quality dynamics. Water quality parameters simulated are 17 in number: Algae, BOD, chlorophyll a, coliforms (fecal, fecal streptococci, total), conservative constituents, DO, nitrogen (ammonia, nitrite, organic), phosphorus (ortho-phosphate, potential), sediment, temperature, TDS, and zooplankton.

The model was applied to the Green River, Washington, with excellent results. Since then, it has also been used in major watersheds in the Seattle and Denver metropolitan areas.

Feigner and Jaworski (11) investigated the Potomac River estuary, using two models to evaluate alternative water quality and wastewater management plans. A time-varying non-tidal model was used to simulate annual and seasonal cycles of nitrogen and phosphorus levels; and a real-time hydrodynamic water quality model, called Dynamic Estuary Model (DEM), produced by Feigner and Harris (10), was utilized to simulate the DO budget, nutrient levels, and salinity distributions. Extensive calibrations of the models were performed on dye data to evaluate dispersion coefficients.

Water quality parameters which the model is capable of simulating comprise: Carbonaceous BOD, chlorophyll a (phytoplankton), DO, nitrogen (inorganic: NH_3, NO_2, and NO_3), phosphorus (inorganic, total). In addition, a number of field studies were conducted to determine the parameters for the reaction rates and the effects of temperature. Simulated and prototype data for the Potomac River were in close agreement. The model was used to determine the allowable nitrogen discharges from existing and proposed waste treatment facilities to maintain chlorophyll a concentrations below nuisance conditions. A DO minimum of 5.0 mg/l was used to determine the allowable oxygen demanding waste discharge to various zones in the estuary.

Chen and Orlob's (4) model is applicable to estuaries, and lakes and reservoirs. For estuaries, the authors constructed a "node-link" geometry, in which nodes (junctions) interact with more than two other elements, and links (channels) with one upstream and one downstream element only. The point of confluence of two streams is occupied by six nodes on their diagram. Links are the equivalent of reaches in other models.

Lakes and reservoirs are sliced horizontally into stratified layers of uniform thickness which are not limited in number. Each slice is assumed uniformly mixed. Hydrodynamic behavior is density dependent, and the model assumed temperature to be the dominant factor for density determination. An implicit solution is used to solve the set of differential equations describing the quality of the lake ecosystem. Input data include hydrology and quality of tributary inflows, the quantity and quality of discharges, outflows, and weather conditions. These can be varied as often as desired. Computations can be performed with a time-step ranging from hours to one day.

Each estuary node or lake layer is treated as a discrete CSTR. Hydrodynamic computations are used to determine the water movement into and out of each hydraulic element. The change in concentration of a constituent or of biota is analyzed and related to the conditions

existing in the reactor. Numerical methods are used to compute the constituent concentration with time.

A large number of parameters are used: Eleven climatic variables, eight geometric factors, six hydrologic elements, 21 quality constituents; in addition, system coefficients include light extinction (2 variables), reaeration (2), decay rate (6), algae (6), zooplankton (7), two groups of fish (12); benthic animals (6 variables), and chemical composition (4). A total of 91 factors are handled by the computer. The 21 quality constituents are: Algae (2 groups), alkalinity, benthic animals, BOD, carbon (total inorganic), CO_2, coliform, detritus, fish (2 groups), DO, nitrogen (NH_3-N, NO_2-N, NO_3-N), pH, PO_4-P, temperature, TDS, toxicity, and zooplankton.

The estuary and lake ecologic models were applied to the San Francisco Bay-Delta System and to Lake Washington, Washington. Results indicated that trends can be simulated. But the true utility of the models to a water resource planner could not be demonstrated because of data limitations.

The last model to be reviewed here is Lombardo's (19) water quality model applicable to lakes, impoundments, and reservoirs. The model assumes the lake to consist of one or two layers with inflows

and outflows entering or leaving the top layer. The water quality dynamics of each layer, assumed to be a CSTR, were computed through the use of a multiple-step explicit solution of partial differential equations describing water quality processes. The time interval was one hour. Seven water quality parameters were simulated: Detritus, DO, nitrogen (nitrate), phosphorus (ortho-phosphate), phytoplankton (chlorophyll a), temperature, and zooplankton.

The model was applied to Green Lake and Lake Sammamish, Washington, for a time period of 200 days. The simulation of Green Lake, essentially completely mixed, was reasonably accurate. Temperature was quite well predicted, and a phytoplankton bloom in midsummer was simulated with the approximate timing and magnitude. A late summer bloom was not predicted. A multi-layered model, instead of the two-layered assumption, would have represented Lake Sammamish more successfully. The mix of coefficients between layers was found to be an extremely sensitive parameter.

Hydrocomp's (20) evaluation of the six models last discussed is that, for rivers, the model by Lombardo and Franz (21) is best because it uses Hydrocomp's Hydrologic Simulation Program (HSP) for quantity. For lakes and reservoirs, Chen and Orlob's (4) model was best because of its multi-layered approach.

When sufficiently perfected, water quality models will permit determining the relative effects of various water quality management schemes on the aquatic environment. Probable consequences should be predicted for a minimum time period of several years. One difficulty is the scarcity of the large numbers of data needed for analysis. It would be helpful to have a checklist of critical water quality events.

The table below shows the variables used in selected water quality models, and the simulation capability of the models.

Variables and Simulation Capability of Selected Water Quality Models

Legend: x = Variable used in modeling

s = Simulation capability of the model

23 Selected Models

Model No.	Developer	Reference No.
1.	Bella	1
2.	Chen and Orlob	4
3.	Dingman and Johnson	5
4.	Di Toro, O'Connor and Thomann	6
5.	Dixon and Hendricks	7
6.	EPA	9 8
7.	Feigner and Jaworski	11
8.	Frankel and Hansen	12
9.	Goodman and Tucker	13
10.	Harper (1972)	17
11.	Jaworski, Weber and Deininger	18
12.	Lombardo (1971)	19
13.	Lombardo and Franz	21
14.	Loucks and Lynn	22
15.	O'Connor	24
16.	O'Connor and Di Toro	25
17.	Simons	28
18.	Texas (DOSAG)	29
19.	Texas (QUAL)	30
20.	Thayer and Krutchkoff	31
21.	Waddell *et al*	32
22.	Weeter	35
23.	White and Tischler	36

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Applicability																							
Rivers and canals				x	x			x	x	x			x	x	x	x		x	x	x	x	x	x
Estuaries		x		x			x																
Lakes & reservoirs	x	x	x			x					x	x	x				x				x		
Type of Model																							
Simulation		x		x	x		x		x	x	x	x	x					x				x	x
Predictive	x					x	x	x						x	x				x	x		x	
Stochastic			x											x						x			
Sensitivity								x		x												x	
Verification	x	x	x	x		x	x		x	x		x	x			x	x			x	x	x	
Meteorology																							
Air temperature		x			x							x											
Atmospheric pressure		x			x							x											
Cloud cover		x																					
Evaporation		x								x		x	x										
Latitude		x																					
Precipitation													x										
Short-wave radiation		x																					
Solar radiation		x								x		x	x										
Wind direction		x																					
Wind velocity		x					x					x											
Geometry																							
Rivers																							
Length		x																					
Width		x																					
Depth		x		x						x	x												
Friction factor		x																					
Lakes																							
Surface area		x																					
Side slope		x																					
Elevation		x																					
Volume		x																					
Hydrology					x																		
Flow		x									x												
Inflow		x										x											
Outflow		x																					
Overflow		x																					
Tide		x																					
Waste discharges		x																					

Model Number

Item	Model Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Water Quality Parameters																							
Physical Indices																							
Benthal deposits															x								
Detritus		x										s											
Sediment													s								x		
Sedimentary phosphorus																					x		
Water temperature	x	s		x		x	x			s	x	s	s				x		x				x
Biological Indices																							
Algae		s					x						s								x		
Benthic algae										s			s										
Benthic animals		s																					
Coliforms		s							x				s								x		
Fecal coliforms													s										
Fecal streptococci													s										
Fish		s																					
Phytoplankton		s		s			s			s		s	s								x		
Zooplankton		s		s								s	s								x		
Inorganic Chemicals																							
Alkalinity		x																					
Ammonia		s		s			s						s								x		
Carbon, inorganic		x																					
Carbon dioxide		x								x													
Chlorides									x														
Dissolved oxygen	x	s		s			s	x	x	s	x	s	s	x	x	x		x	x	x	x	x	x
Heavy metals																					x		
Nitrate		s		s			s			s		s	s								x		
Nitrite		s		s			s						s								x		
pH		s								s													
Phosphate		s		s			s			s		s	s										
Phosph[illegible] [illegible]										s											x		
TDS		s	x	s			s			s			s				x		x				x
Organic Chemicals																							
Carbon, organic																					x		
Carbon, refractory																					x		
Nitrogen, organic													s								x		
Pesticides																					x		
Phosphorus																					x		

Item	Model Number																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Combined Chemicals																							
Phosphorus, total		x					s						s										
Toxicity		x																			x		
Waste-assimilative capability			x																				x
Natural Phenomena																							
Aeration, natural	x	x					x			x			x		x						x		
BOD		s		s			s			s	x	s	s										
BOD decay									x				x	x					x	x	x	x	x
BOD, benthic	x						x	x		x		x	x								x		
BOD, carbon							x														x		
BOD, nitrogen							x														x		
BOD, sedimentary								x													x		
Cross-river variability															x								
Currents																	x						
Denitrification													x										
Digestive efficiency		x					x			x		x	x										
Dispersion, horiz.										x													
Dispersion, vert.	x																x						
Eutrophication				x																			
Excretion		x		x									x										
Grazing				x								x									x		
Growth		x		x			x			x		x	x								x		
Half-saturation		x																					
Heat transfer										x		x											
Mortality		x										x	x										
Nitrification				x									x										
Oxidation, carbon and nitrogen															x								
Photosynthesis	x			x		x	x	x		x		x	x		x	x					x	x	
Reaction rate								x															
Respiration	x	x		x			x			x		x	x		x						x		
Stratification	x					x											x						
Water velocity							x							x	x					x			
Artificial Phenomena																							
Aeration, artificial															x								
Discharges, time-varying					x			x						x						x		x	
Flow augmentation																			x			x	

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CHAPTER IV. TECHNOLOGY AND COST OF WATER SUPPLY PURIFICATION

How can American water resources be rendered fit for use as water supply, and at what cost? In planning for optimal water allocation to a variety of users, it is well to have options of alternative technologies and outlays whereby suitable water quality levels may be achieved and maintained. Among the technologies reviewed, the design and construction of gravity reservoirs for water quality storage is quite familiar to the Corps of Engineers. Other opportunities exist that appear susceptible of utilization by the Corps: artificial instream aeration, pumped quality storage, aquifer recharge through treated wastewater injection, and raw water desalination. The principal technologies for upgrading water supply quality, with their respective price tags, are discussed in this chapter.

A. Instream Water Purification

Water quality requirements for waste assimilation were investigated in Chapter II, C, 5. The natural assimilative and self-purifying capacity of a water resource will next be reviewed; it can be supplemented by artificial instream reaeration.

1. Natural Reoxygenation

Several authors have endeavored to measure self-purification capacity by means of non-stochastic prediction of DO balances in water.

Probability analysis, essential to this approach, was omitted. According to Purdy (1), for example, the oxygen balance, in each reach of a stream, equals the inflowing DO, minus deoxygenation (fresh BOD, sludge deposits, biological extraction, and oxygenation of nitrogenous substances to nitrates), plus reoxygenation (governed by occupied channel volume, mean water depth, mean water temperature, and stream turnover). The DO percent of saturation can be plotted on a chart against miles from river mouth.

A more comprehensive formula for stream self-purification was presented by Deloach and Tsivoglou (2), who included photosynthesis and oxygen transfer with natural reaeration and water temperature. The reaeration component of self-purification was investigated by Isaacs and Gandy (3) who developed a formula for determining the reaeration rate constant k_2:

$$k_{2(T^\circ)} = 3.739 \frac{V}{H^{3/2}} (1.0241)^{T-20}$$

where $k_{2(T^\circ)}$ = the reaeration rate constant (in day $^{-1}$) at any temperature.

V = the average stream velocity, in feet/sec.

H = thaverage stream depth in feet.

Thackston and Krenkel (4) proposed a somewhat different formula. The reaeration coefficient, they concluded, is proportional to the vertical mass transfer coefficient at the surface, and inversely proportional to the square of the average depth. Their equation, after

refinement and simplification, reads:

$$k_2 = 0.000125\ (1 + F^{1/2})\ \frac{u^*}{h}\quad, \text{ where}$$

k_2 = reaeration coefficient

F = Froude number = $\frac{u}{\sqrt{gh}}$

u^* = shear velocity

h = depth

g = acceleration due to gravity

u = velocity in a given direction

This equation, when applied by the authors to various scales of flow, was found more accurate, covered a wider range of flow scales, and was less sensitive to variations in basic data than any of the previously used methods of prediction.

A mechanized instream aerator was used by Shieh and Davidson (5) to determine the natural reaeration coefficient. Operating the aerator in a sinusoidal fashion with a known amplitude and frequency, they used it as a boundary condition in conjunction with a detailed one-dimensional, unsteady-state Streeter-Phelps model of a polluted river. Field measurements of the natural reaeration coefficient became possible after the authors succeeded in uncoupling the natural reaeration coefficient from: (a) the biochemical removal coefficient, (b) the benthal demand factor, and (c) the respiration term. However, no uncoupling of the natural

reaeration coefficient from the photosynthesis factor was achieved. Nevertheless, the authors feel that the use of single-station mechanical aerators in polluted rivers is a promising new water quality monitoring device.

Whipple (6), who has done much pioneering research with artificial aerators, showed that, for medium-sized streams under summer-flow conditions, the natural reaeration coefficient varies by a factor of 4.

2. Artificial Reaeration

Natural self-purification can be accelerated or intensified by various artificial aeration devices. Whether artificial aerators are considered as substitutes for, or merely as adjuncts to, waste treatment facilities, they have the great advantage of operating on all collective wastes -- not just recorded outfalls.

Four types of instream aerators, their performances, capital investments and operating costs, were described by Whipple, Coughlan and Yu (7):

(a) Mechanical surface aerators, sold with a guaranteed efficiency of 4 lbs. of DO added per shaft-HP per hour of operation, usually have a much lower actual performance. Efficiency increases slightly with flow velocity. A somewhat higher oxygen transfer rate may be obtained through the installation of a flow concentration device. Capital and annual costs are:

Electric Mechanical Surface Aerator Costs

Units in Configuration	Horse-Power per Unit	Horse-Power per Configuration	Capital Cost ($)	Total Annual Cost($)
3	75	225	132,000	41,500
6	75	450	263,000	72,900
9	75	675	391,000	102,000

(b) Submerged air diffusers aerate by releasing fine bubbles. Subject to clogging, they have not come into general use. Oxygen transfer rates per shaft-HP per hour equal about two-thirds of those of mechanical surface aerators. Their costs are calculated from approximate proportions given in the article:

Electric or Diesel Diffusion Aerator Costs

Units in Configuration	Horse-Power per Unit	Horse-Power per Configuration	Capital Cost ($)	Total Annual Cost($)
4	80	320	198,000	52,000
8	80	640	395,000	91,000
12	80	960	587,000	128,000

(c) Pure oxygen diffusers are of questionable reliability: claims made for them have not been substantiated. No costs are available.

(d) Hydroelectric turbines equipped for air admission are applicable only in special situations. Costs were not estimated.

The oxygen transfer rate varies directly with the oxygen deficit, i.e., the difference between DO saturation and actual concentration, and in less obvious ways with water quality and temperature. Unless a very complete BOD study is made, the spacing of sites might be at one-mile intervals. Whipple and Yu (8) added that whether surface aerators or bottom air diffusers are applicable to a given site depends primarily upon the requirements of navigation. For critical areas of the Delaware estuary, the cost of obtaining desired DO concentrations through artificial aeration is estimated to be less than one-third of the cost of achieving the same result through waste treatment only.

The latter statement was corroborated by Kneese and Bower (10), quoting Davis (9), when they presented comparable costs of meeting the 4 ppm of DO objective in the Potomac estuary:

Reoxygenation	$ 29,000,000
Effluent Distribution (staggering)	85,000,000
Low-Flow Augmentation	115,000,000

These costs are present worth (1965 dollars) of capital, operating, and routine maintenance, discounted at 4% for a 50-year life. Costs of processes other than low-flow augmentation are based on 2.5 months of operation per year. Multiple-process solutions are also listed, with costs ranging from 22 to 146 million dollars. Reoxygenation appears costwise competitive with most other systems.

A full-scale operation of mechanical aerators on a small polluted river was reported by Hunter and Whipple (11). The experiment confirmed the economy of instream aeration. Treatment of recorded effluents would have to be 98.5% efficient and remove 65% of the ammonia content to achieve a DO concentration of 4 mg/1, whereas a string of twenty-two 75-HP aerators could accomplish the same result at one-third the cost.

Hogan, Reed, and Starbird (12) investigated what types of aeration devices were most suitable for oxygenating various water bodies. For a stream, mechanical aeration was found most appropriate. For a lake, air diffusion was judged most effective; however, for intermittent destratification and aeration, they recommended a large diameter ducted propeller to draw up bottom water, in conjunction with a mechanical surface aerator.

Huckabay and Keller (13) experimented with a gravity-flow aerator, consisting of a washboard-type river-bed covering made of transversely corrugated galvanized iron, with a sinusoidal characteristic of 1.25 inch amplitude. Oxygen transfer was found to be a function of the angle of inclination, but not of flow rate. The cascade board appeared to the authors as an aeration method deserving of wide-spread consideration. It would have minimal operating costs, and would not impede navigation.

B. Year-Round Waste Dilution Through Water Quality Storage

Minimum river flow and waste dilution can be jointly assured on a year-round basis through the operation of storage reservoirs. Water quality storage, as a single-purpose project, would rarely be justified economically. But where it can be partly subsidized by a water-supply, flood-control, drought-insurance, and/or recreational project, marginal benefits may exceed marginal costs, or at least the aggregate benefit-cost ratio may still exceed unity.

1. Gravity Storage

Benefits of flow augmentation for water quality [illegible] be measured, wrote Carter, Haney and Pyatt (14), by the cost avoided of downstream collective waste treatment. That cost increases rapidly in the upper ranges of BOD removal. When storage construction costs are shared with one or more additional purposes, and DO standards require high BOD removal, flow augmentation may well be competitive. The quality of the mixed water is a function of the reservoir layer from which the incremental water is removed. In one example, the additional flow, drained from lower reservoir layers, had zero DO. Flow augmentation benefits were positive up to an increment of 430 mgd, negative thereafter. Minimum costs occurred when the flow was augmented by 133 mgd, an amount of zero DO water which could be assimilated by the river water.

Heidelberg College (19) investigated the Sandusky River in Ohio to establish relationships between volume and quality of augmented low flow. Fluoride, calcium, magnesium, and sodium concentrations were found directly correlated with flow volume; total and soluble phosphorus content, indirectly. No correlation was observed between the flow and concentrations of potassium or nitrates. Oxygen content was high at an abundant flow, but varied with algal populations, which were reduced by flow velocity.

Mathematical models of low flow augmentation where quality storage is the reservoir's only purpose, were developed by Perez, Schaake and Pyatt (16), Loucks (17) (a stochastic model), and Bayer (18). Several additional models pertaining to reservoir operation for water quality are discussed in Chapter VII, B.

Reservoir construction and O + M costs are very familiar to the Corps of Engineers. Nevertheless, it may be convenient to have simplified tables and equations available for preliminary estimates.

The Standardized Procedure for Estimating Costs of Conventional Water Supplies, a Manual prepared by Black & Veatch (24) under sponsorship of the U. S. Office of Saline Water, contains cost tables applicable to the construction, operation and maintenance of impounding reservoirs.

The experienced average day demand for the most recent year, in mgd, is multiplied by a design capacity ratio varying from 1.2 (100 mgd

with an estimated 0-10% system growth per decade) to 5 (0.1 mgd with 30-50% growth). This is the desired yield of the reservoir. The storage-yield relationship is given in the following table. The dependable annual yield required (R) in mgy is divided by the average annual stream flow (Q) in mgy, and the table gives for this ratio the ratio of the design reservoir storage capacity (C) in million gallons divided by the average stream flow (Q) in mgy. The design reservoir capacity (C) is obtained by multiplying the second ratio in the table by the average annual stream flow (Q).

Impounding Reservoir Storage-Yield Relationship

R/Q	C/Q	R/Q	C/Q
.04	.015	.35	.93
.06	.03	.40	1.3
.08	.05	.45	1.3
.10	.07	.50	2.5
.15	.15	.55	3.5
.20	.27	.60	4.8
.25	.43	.65	6.7
.30	.64	.70	9.7

R = Dependable annual yield required

Q = Average annual stream flow

C = Design reservoir capacity

The following table lists reservoir construction costs related to reservoir design capacity.

Impounding Reservoir Construction Cost

Storage Capacity (bill. gall.)	Cost ($1000)	Storage Capacity (bill. gall.)	Cost ($1000)
0.1	200	30	7,700
0.2	300	40	9,150
0.5	600	50	10,450
1.0	950	60	11,600
2	1,500	70	12,750
5	2,600	80	13,800
10	3,950	90	14,800
20	6,000	100	15,800

Construction costs are trended by multiplying them by the current Engineering News Record Building Cost Index and dividing by 584, the index for the January 1963 base period.

Land to be acquired for the reservoir may be estimated as 1.5 times the reservoir surface area at spillway level. Land costs may be determined on the basis of $100 per acre if a more appropriate current figure reflecting local values is not known. The surface area of a reservoir may be derived from its storage capacity, as follows:

Impounding Reservoir Surface Area

Storage Capacity (bill. gall.)	Area (acres)	Storage Capacity (bill. gall.)	Area (acres)
0.1	35	30	4,100
0.2	75	40	5,100
0.5	180	50	6,000
1.0	320	60	6,800
2	560	70	7,600
5	1,070	80	8,400
10	1,800	90	9,200
20	3,000	100	10,000

Capital investments are subject to a 10% supplement for engineering, administrative, and financing costs. Interest during construction is added at the rate of one-half the interest rate of the project loan for one year.

Reservoir operation and maintenance costs may be estimated at \$0.007 per 1000 gallons produced.

Operation and maintenance costs are trended by multiplying them by the average hourly earnings of production workers for "Water, Steam, and Sanitary Systems," in Table C-1 (Transportation and Public Utilities) of the "Monthly Labor Review" published by the Bureau of Labor Statistics, U. S. Department of Labor, and dividing by \$2.37, the average hourly earnings for January 1963.

Another source of impoundment reservoir cost data is the report which the Pennsylvania State University (21) prepared for the Corps of Engineers under the title of "A Method for Integrating Surface and Ground Water Use in Humid Regions." Their cost functions follow:

Reservoir Construction, Operation and Maintenance Costs

Item	Capital Investment	Life	O + M Costs
Reservoir	$\$ = (IR)\ (9{,}160)$	50 yr	$\$/yr = (IR)\ (3{,}420)$
	$(a/f^{0.54}) + (0.49)$ (land cost)		$(10)^{0.000066 \times a/f}$
	$(a/f^{0.87})$		IR = 1.98
	IR = 1.84 Land Value = \$500 per acre		

IR = Index Ratio whereby costs may be updated to midyear 1972 levels when the Engineering News Record Building Cost Index (ENR-BCI) stood at 1039. For further updating, multiply by the current index and divide by 1039.

Costs of conveying water from reservoir to water plant may be found under "Water Importation" (Section C, 2).

2. Pumped Storage

Contrary to gravity storage, pumped storage has a substantial operating cost. All the more reason for pumped quality storage to remain ancillary to other pumped storage purposes. In the case of pumped storage, one additional function may contribute to making quality storage economically viable: power storage. Water is pumped up daily during hours of low power demand, and released in peak power demand periods, much of the power being recuperated. Water storage has a seasonal rhythm -- the demand for non-storable electric power, a diurnal rhythm. Quality storage water can be pumped up during successive nights, and released every day during peak power demand hours. Because of hourly power rate differentials, most, all, or more than all of the power costs are recovered.

According to Velz et al (20), pumped storage has these advantages over gravity storage: More sites are available for pumped than for gravity storage reservoirs, because pumped storage reservoirs do not depend for replenishment on tributary drainage areas. Instead of being located in the upper reaches of a watershed, hours or days of water

travel time removed from populated areas, pumped storage can be sited downstream, near areas in need of water supply, drought control, and year-round water quality.

Pumped storage reservoirs assure higher quality water than gravity storage reservoirs. The daily cycling of large volumes of water displaced by power generation and back-pumping virtually eliminates stratification, insuring cool water with consistently high DO content. In gravity storage reservoirs, water released from upper layers is too warm; the DO in water drained from lower layers approaches exhaustion. This affects the river's self-purifying capacity. In Ohio's Miami River Basin, pumped storage with a yield of 150 cfs can maintain the state-recommended standard of 4 ppm of DO, which otherwise would require gravity storage in the headwaters with a yield of 300 cfs.

Conjunctive operation of gravity and pumped storage reservoirs expands the flexibility needed to insure stable gravity reservoir levels for water-based recreation throughout the summer season. It may also be cheaper than gravity storage alone, as shown in the following comparative table:

Savings from Joint Operation of Gravity and Pumped Storage

Item	Unit	Storage System Gravity	Storage System Joint	Savings
Water Required	a/f	262,000	188,000	74,000
from pumped storage		-	80,000	
from gravity storage		262,000	108,000	

Savings from Joint Operation of Gravity and Pumped Storage
(continued)

Item	Unit	Storage System Gravity	Storage System Joint	Savings
Power Required	KW	721,000	700,000	21,000
from hydro-power		-	325,000	
from local steam power		-	375,000	
from distant steam power		721,000	-	
Capital Cost -- Water	$1000	34,562	38,000	-3,438
pumped storage		-	25,000	
gravity storage		34,562	13,000	
Capital Cost -- Power	$1000	80,500	64,000	16,500
hydro-power		-	26,500	
local steam power		-	37,500	
distant steam power		80,500	-	
Total Capital Cost	$1000	115,062	102,000	13,062
Annual Cost -- Water	$1000	2,246	2,470	-224
pumped storage		-	1,625	
gravity storage		2,246	845	
Annual Cost -- Power	$1000	19,595	16,910	2,685
hydro-power		-	3,740	
local steam power		-	6,000	
distant steam power		13,320	-	
assoc. power costs		6,275	7,170	
Total Annual Cost		21,841	19,380	2,461

C. Upgrading Raw Water Quality

The need for improving the quality of raw water for use as public water supply for a variety of purposes is manifest from the elaborate raw water quality criteria and drinking and other water standards

reviewed in Chapter II. True, raw water quality criteria can help select from among alternate sources those most appropriate for the intended use. In many instances, however, they merely point out the existing quality gap between water nature provides and water users need. Water quality standards were established because often raw water cannot be treated routinely and inexpensively by available technology to produce a high quality public water supply.

Raw water quality can be upgraded in several ways. Two approaches involve the source, two others the treatment technology.

1. Conjunctive Use of Surface and Ground Water

Frequent differentials in quality characteristics make surface and ground water potential complements in achieving desirable levels of purity. In general, surface waters collect precipitation but also all sorts of wastes, ending up soft but in need of routine treatment. Groundwater, not so subject to miscellaneous pollution, is in more intimate contact with various minerals present in rock formations; it is frequently high in salt content, particularly in hardness, but low in other impurities. There are situations in which conjunctive use of surface and ground water can offset the disadvantages of both.

Such opportunities were investigated by the authors of a Pennsylvania State University study (21) mentioned earlier, which was aimed at

developing a method for integrating surface and ground water use. A sensitivity analysis brought forth the following general conclusions:

Integrated use schemes under certain circumstances are economically advantageous over single source development. Whether integrated use is feasible or not depends on the relative cost competitiveness between surface and groundwater sources. The single most important cost factor is the water quality and treatment need of the source. Where each of surface and groundwater is adequate in volume to meet the maximum day demand and is otherwise competitive, with surface water requiring turbidity removal and groundwater involving only chlorination, groundwater alone is indicated. Integrated use is the most economical alternative where surface requires turbidity removal and groundwater would need softening, provided the hardness of surface water is less than the permissible limit. Under those conditions, a mixing ratio can always be found that will make the softening of groundwater unnecessary. The surface water is subjected to turbidity removal before blending with groundwater, chlorination being administered to the blend. Integration of the two sources is also recommended where surface water needs only chlorination and groundwater requires softening, again provided surface water hardness is less than the limit. Finally, integrated use is the most economical alternative whenever both sources require the same treatment. Surface water alone is not recommended.

Well supply costs are presented in the Black & Veatch Manual (24). The maximum day demand experienced during the past 10 years, in mgd, is multiplied by a design capacity ratio varying between 1.3 (100 mgd with an estimated 0 - 10% system growth per decade) and 2.8 (0.1 mgd with 30 - 50% growth). This is the desired yield. Costs follow:

Well Construction Cost

Well Field Capacity (mgd)	Cost ($1000)	Well Field Capacity (mgd)	Cost ($1000)
0.1	20	30	750
0.2	21	40	1,000
0.5	26	50	1,250
1.0	34	60	1,500
2	50	70	1,750
5	125	80	2,000
10	250	90	2,250
20	500	100	2,500

Construction costs may be trended in accordance with directions given above for reservoir costs (Section B, 1). Trended costs are subject to a 10% supplement for engineering, administrative, and financing services. The land needed for the well field is estimated to cost 2% of the trended construction cost. Interest during construction is estimated at the rate of one-half the interest rate of the project for one year.

Well supply operating and maintenance costs may be estimated at $0.007 per 1000 gallons of water produced. To this must be added pumping O + M costs, as follows:

Pumping O + M Costs
(exclusive of power)

Average Quantity of Water Produced (mgd)	Cost ($/Kgal)	Average Quantity of Water Produced (mgd)	Cost ($/Kgal)
0.1	.050	30	.008
0.2	.039	40	.008
0.5	.027	50	.007
1.0	.020	60	.007
2	.015	70	.006
5	.012	80	.006
10	.011	90	.006
20	.009	100	.005

Power costs must be added at the rate of $0.004 per 1000 gallons produced for each 100 feet of static and friction head to be overcome. Pumping lift is estimated at 300 feet below ground, plus 100 feet for water pressure.

Operation and maintenance costs may be trended in accordance with directions given above for reservoir O + M costs (Section B, 1).

Pennsylvania State University's (21) groundwater development and O + M costs follow:

Groundwater Development, Operation and Maintenance Costs

Item	Capital Investment	Life	O + M Costs
Well	\$ = (IR) (COE*) (ft. $\text{depth}^{\text{EXP*}}$) + 4500 IR = 1.6	40 yr	-
Well Pump	\$ = (IR) (7.31) ($\text{gpm}^{0.453}$) (ft. $\text{height}^{0.642}$) IR = 1.6	20 yr	\$/yr = (IR) (7.6) (mgy) IR = 1.7
Booster Pump	\$ = (IR) (67.8) (gpm) - (4.04) (gpm^2) + (0.123) (gpm^3) (ft. head - 700 ft) IR = 1.7	20 yr	
Electric Power	-		\$/yr = (IR) (1.0525) (215 + (1.61) (KW demand - 100) + 190 + (0.007) (KWH/mo - 20,000)) + (IR) (0.00023) (KWD) IR = 1.00

* Coefficients (COE) and Exponents (EXP) For Well Costs

Geological Formation	Bore Hole Diam (in)	COE	EXP
Tubular wells finished in sand and gravel	6 - 10	800	0.299
	12 - 15	850	0.373
Gravel-packed wells finished in sand and gravel	16 - 20	680	0.408
	24 - 34	680	0.482
	36 - 42	890	0.583
Shallow sandstone, limestone or dolomite bedrock wells	6	578	1.413
	8 - 12	839	1.450
	15 - 24	1781	1.471
Deep sandstone wells	8 - 12	29	1.870
	15 - 19	1314	1.429

For updating, see the note pertaining to reservoir costs (Section B, 1).

When water from two sources with several dissimilar critical quality parameters is to be mixed, three cases may be distinguished:

Case 1. One or the other water source meets all the standards. No blending is necessary.

Case 2. For each parameter, one or the other source meets the corresponding quality standard; in addition, for each parameter, a is smaller than 2s - b, where

a = Parameter concentration in source with higher content;

b = Parameter concentration in source with lower content;

s = Standard permissible concentration of parameter.

In that case, an equal amount of water from both sources (and a limited number of other ratios) meet all standards.

Case 3. For each parameter, one or the other source meets the corresponding standard; for one or more parameters, a is greater than 2s - b. A solution may be possible. Establish, for each parameter, the range of mixes that will produce water of acceptable quality. If all ranges overlap, a solution (or a limited number of solutions) is possible. If two or more ranges are incompatible, no solution can be found.

Ranges are computed as follows for each parameter. The range for the source with the higher parameter concentration is:

$$0\% \text{ to } \frac{100(s-b)}{a-b}\ \%$$

For the other source, the range is complementary:

$$\frac{100(a-s)}{a-b} \% \text{ to } 100\%$$

Here is an example of compatible and incompatible parameters:

Ranges of Blending Proportions for Two Sources and Several Parameters

Parameter	Concentration			Blending Range	
	Source 1	Standard	Source 2	Source 1	Source 2
A	4	8	10	33 - 100%	0 - 67%
B	60	50	24	0 - 72%	28 - 100%
C	6	8	12	67 - 100%	0 - 33%
Combined		Compatible		67 - 72%	28 - [illegible]%

Addition of Parameter D

D	0.18	0.1	0.05	0 - 61%	39 - 100%
Combined		Incompatible		No solution	

Where no solution can be found through any blending proportions, it may be desirable to compute the damages associated with the use of water of substandard quality with a view to minimizing it, or to find a combination of blending and treatment that will minimize costs.

Where three or more sources are available for blending, linear programming may be applicable. A generalized formula is presented in Chapter VII, Section C, 2.

One other use of groundwater deserves mention at this point. Frankel (22), after examining the economics of advanced waste treatment (AWT) systems and recycling schemes, concluded that artificial groundwater recharge using treated municipal wastes presents the most feasible solution to effluent reclamation. Artificial recharge provides the quantitative flexibility needed in using aquifers, prevents mining or a lowering of the water table, as well as land subsidence. It may even avoid sea water intrusion in coastal areas. Frankel also discussed a proposed scheme for supplementing the use of surface water as a supply for Washington, D. C. through artificial recharge and development of nearby aquifers.

2. Water Importation

When a community needs incremental water supply, it is time to investigate new sources of water of superior quality. And without waiting to be faced with possible water shortages, those cities and towns now using substandard quality water should do likewise. Unlimited water resources of excellent water quality are accessible everywhere in the U. S. -- at a price. Water importation may involve the conveyance of water supply from a lake two miles distant, or it may range over hundreds of miles, as does California's Feather River Project, or the Ralph M. Parsons Company's proposed NAWAPA project.

The quality of New York City's 1.2 bgd water supply is excellent. The municipal engineers had reached out as far as 200 miles from the

city to tap streams of high purity. Now, with continually increasing needs, a source long rejected because its quality did not measure up to desired levels is being considered: the Hudson River.

Mitchell (23) explained this change of heart. With better pumping and treatment technology available today, the city can afford a certain amount of blending. In the past, upland waters could be delivered by gravity and without treatment other than chlorination. The Hudson River has a tidal salinity and an upstream pollution problem. By providing storage to augment river flow in dry periods, a fifty-year supply can be developed as a wholly upland, gravity-conveyed supply, or it may be released from upland reservoirs and pumped out of the lower Hudson River at or above Hyde Park. The latter is the least cost solution.

It is difficult to suggest water importation costs in the abstract. Water conveyance may involve rock excavation, tunneling, bridging, channeling, piping, and pumping. Costs vary with terrain and climate. Nevertheless, average construction, and operation and maintenance costs of surface transmission pipelines and pumping facilities can be estimated. The following cost data are extracted from the Black & Veatch Manual (24):

The maximum day demand experienced during the last 10 years is multiplied by a design capacity ratio varying from 1.5 (100 mgd with an estimated 0 - 10% system growth per decade) to 5 (0.1 mgd with 30 - 50% growth). This is the design capacity of the pipeline. The following table presents the costs per mile:

Construction Cost of Transmission Pipeline

Flow Required (mgd)	Pipe Diameter (inches)	Cost per Mile ($1000)
0.1	4	24
0.2	6	29
0.3	8	35
0.5	8	35
1.0	10	41
2	12	48
3	16	65
4	20	83
5	20	83
7.5	24	103
10	24	103
12.5	26	114
15	28	125
17.5	30	136
20	32	146
25	34	156
30	36	167
35	38	178
40	40	190
45	42	201
50	44	212
55	46	225
60	48	237
70	50	250
80	52	261
90	56	288
100	58	301

If the source of supply of raw water is not at an elevation adequate for gravity flow to the point of discharge, it is necessary

to pump the water to overcome static lift as well as friction losses in pipelines. To determine the number of pumping stations required, three inputs are needed:

Es = Ground elevation at source;
Ed = Elevation at point of discharge;
SD = Length from source to discharge in 1000 feet.

Three cases are possible:

1. $\frac{Es-Ed}{SD}$ = 4 or over: no pumping is needed;

2. $\frac{Es-Ed}{SD}$ = 0 - 4: pumping is required; Number of pumping stations = $\frac{(4xSD) - (Es-Ed)}{400}$

3. $\frac{Ed-Es}{SD}$ = positive: pumping is required; Number of pumping stations = $\frac{(4xSD) + (Ed-Es)}{400}$

Once the number of pumping stations is known costs can be applied:

Construction Cost of Pipeline Pumping Stations

Design Capacity (mgd)	Construction Cost ($1000)	Design Capacity (mgd)	Construction Cost ($1000)
0.1	37	30	605
0.2	40	40	770
0.5	50	50	920
1.0	67	60	1080
2	94	70	1235
5	160	80	1390
10	256	90	1550
20	438	100	1700

Construction costs may be trended in accordance with directions given above for reservoir costs (Section B. 1). Add to this a 10% supplement to cover engineering, administrative, and financing services. The prevailing regional right-of-way cost per mile should be included; if not available, add $2,500 per mile. Interest during construction may be computed at one-half the interest rate for the project for one year.

Annual operation and maintenance costs for the transmission pipeline are 0.25% of the trended construction cost. Those for pumping combine two items: an O + M cost per 1000 gallons for each pumping station, plus a pumping power cost. The O + M cost for pumping is tabulated below:

Pumping O + M Cost Exclusive of Power

Average Quantity of Water Produced (mgd)	O + M Cost (¢/Kgal)	Average Quantity of Water Produced (mgd)	O + M Cost (¢/Kgal)
0.1	5.0	30	0.8
0.2	3.9	40	0.8
0.5	2.7	50	0.7
1.0	2.0	60	0.7
2	1.5	70	0.6
5	1.2	80	0.6
10	1.1	90	0.6
20	0.9	100	0.5

The pumping power cost is estimated at $0.004 per 1000 gallons for each 100 feet of static and friction head to be overcome. Total O + M

costs must be trended as explained under Reservoirs (Section B, 1).

Comparable cost figures from the Pennsylvania State University study (21) are as follows:

Pipeline and Pumping Installation, Operation and Maintenance Costs

Item	Capital Investment	Life	O + M Costs
Pipeline	\$/mi = (IR) (2,160) (in.diam$^{1.29}$) IR = 1.70	50 yr	\$/yr = (0.0025) (construction cost)
Pumping station	For 0.2 - 2.0 mgd: \$ = (IR) (HP) (0.29) (gpm$^{-0.5}$) For 2.0 - 200 mgd: \$ = (IR) (HP) (4.19) (gpm$^{-0.12}$) IR = 1.70	25 yr	For 150-15,000 HP: \$/yr = (IR) (0.311) (gpm$^{0.54}$) (ft.height$^{0.41}$) (hrs/yr$^{0.43}$) (yr.plant age$^{0.55}$) IR = 1.79
Electric power	-		\$/yr = (IR) (1.0525) (215 + (1.61) (KW demand - 100) + 190 + (0.007) (KWH/mo - 20,000)) + (IR) (0.00023) (KWD) IR = 1.00

For IR, see the note under Reservoirs (Section B, 1.).

3. Conventional Raw Water Treatment

Processes used in conventional raw water treatment, i.e., treatment not involving desalination, include:

Basic Processes

1. Coagulation
2. Flocculation
3. Sedimentation
4. Clarification
5. Filtration
6. Disinfection

Auxiliary Processes

1. Algae and weed control
2. Softening (lime, lime-soda, or ion exchange)
3. Iron and manganese removal
4. Taste and odor control
5. Fluoridation and defluoridation
6. Detergent control
7. Herbicide and pesticide control
8. Radioactivity removal
9. Antiscale and anticorrosion treatment
10. Sludge disposal

Wanielista and Falkson (25) advocated flexibility in the design of raw water treatment plants. Some economic efficiency should be sacrificed to avoid a steep increase in average water cost when quantitative and qualitative supplies or requirements change. Excess capacity is advocated; other recommended design features include: variable-rate chemical feeders, variable flow-rate controls, parallel units, variable application points for chlorine, increased capacity

clear wells, and recirculation. When quality fluctuates, such provisions may obviate the need for costly heroic measures.

In a study of virus removal, Sproul (26) presented results of experiments with a variety of viruses and treatment processes. Coagulation is sufficient to remove 99.8% of Phage T4 and Phage MS2; excess lime soda ash softening removes 99.9%, and ozone in a concentration of 1.27 mg/l inactivates 99.99% of Poliovirus Type I. Virus inactivation by pH between 10.5 and 12.2 is ineffective.

Mackenthun and Keup (27) presented results of a survey of biological problems encountered in water supplies. Frequently reported problems were algae and pond weeds in surface sources, iron bacteria in wells and pipes, tastes and odors, filter clogging, and animals. Physical control methods used were screening, microstraining, mechanical cleaning, flushing, reservoir aeration, pond weed cutting, and filter rate adjustment; most frequently used chemicals were chlorine, copper sulfate, carbon, and potassium permanganate. Another study showed algal growths to be effectively checked by application of 2 ppm of copper sulfate.

The previously mentioned Black & Veatch Manual (24) presents construction and O + M costs of treatment plants, including treated water storage.

The maximum day demand experienced during the last 10 years is multiplied by a design capacity ratio which varies between 1.2 (100 mgd with an estimated 0 - 10% system growth per decade) and 4 (0.1 mgd with 30 - 50% growth). This determines the required design capacity.

Construction Cost of Treatment Plant and Storage

Design Capacity (mgd)	Construction Cost ($1000)	Design Capacity (mgd)	Construction Cost ($1000)
0.1	60	30	2,700
0.2	90	40	3,400
0.5	140	50	4,000
1.0	220	60	4,600
2	380	70	5,100
5	700	80	5,600
10	1,150	90	6,100
20	2,000	100	6,550

These costs include softening where required. Treated water storage is likewise included -- to the extent of 25% of the plant design maximum day capacity. To the trended capital cost should be added the 10% supplement for overhead costs, 2% for land acquisition, and the interest during construction. For details, see Reservoirs (Section B, 1).

Annual O + M Costs are as follows:

Water Treatment O + M Costs
Exclusive of Chemicals and Power

Average Quantity Treated (mgd)	O + M Cost (¢/Kgal)	Average Quantity Treated (mgd)	O + M Cost (¢/Kgal)
0.1	12.0	2	4.8
0.2	10.2	5	3.4
0.5	7.8	10	2.8
1.0	6.2	20	2.4

30	2.2	70	1.8
40	2.1	80	1.8
50	2.0	90	1.7
60	1.9	100	1.7

The cost of chemicals used in the treatment plant follows:

Treatment Process	Cost of Chemicals (¢/Kgal)
With softening	3.0
Without softening	
Supply from flowing river or stream	1.8
Supply from other source	0.9
Disinfection only (no other treatment)	0.4

Treated water pumping equivalent to a 250-ft head, and corresponding power are required for distribution pressure.

Total O + M costs of treatment and chemicals are trended as previously indicated (See Section B, 1).

The Pennsylvania State University study (21) presents the following set of raw water treatment costs:

Raw Water Treatment Costs

Item	Capital Investment	Life	O + M Costs
Chlorination when no other treatment is needed	\$ = (IR) (87,000) ($mgd^{0.6}$) IR = 1.00	50 yr	\$/yr = (IR) (28.8) (0.13) (mg) + (0.50) (mg) + (0.02) (construction cost) IR = 1.24

Item	Capital Investment	Life	O + M Costs
Lime-soda softening	For 1 - 10 mgd: \$ = (IR) (310,000) ($mgd^{0.55}$) For over 10 mgd: \$ = (IR) (151,000) ($mgd^{0.862}$) IR = 1.62	50 yr	\$/yr = (IR) (365) (COE*) (AYFR in mgd ^{EXP*}) IR = 1.62 AYFR = average yearly flow rate (in mgd)
Coagulation, flocculation and rapid sand filtration	\$ = (IR) (330,000) ($mgd^{0.678}$) IR = 1.62	50 yr	\$/yr = (IR) (365) (COE**) (AYFR in $mgd^{0.62}$) IR = 1.62 AYFR = average yearly flow rate (in mgd)
Operation building ***	\$ = (IR) (40,000) ($mgd^{0.7}$) IR = 1.88	50 yr	\$/yr = (0.02) (construction cost) + (IR) (28.8) (0.13) (mgd) IR = 1.24
Buried concrete reservoir	\$ = (IR) (67,000) (capacity in $mg^{0.606}$) IR = 2.03	50 yr	\$/yr = (IR) (860) ($mg^{0.211}$) IR = 2.03

* Coefficients (COE) and Exponents (EXP) for Lime-Soda Softening O + M Cost

Hardness Reduction (mg/1)	Range of AYFR (mgd)	COE	EXP
100	1 - 10	147.0	0.530
100	10 - 100	53.0	0.919
200	1 - 10	162.0	0.585
200	10 - 100	71.4	0.919
300	1 - 10	174.0	0.632
300	10 - 100	87.0	0.919

** Coefficients (COE) for Coagulation, Flocculation, and Rapid Sand Filtration O + M Cost

Average Annual Turbidity (ppm of SiO_2)	COE	Average Annual Turbidity (ppm of SiO_2)	COE
100	78.0	40	57.2
90	75.0	30	53.7
80	71.2	20	51.2
70	68.0	10	47.5
60	65.0	0	45.0
50	61.2		

*** An operation building is not needed where chlorination is the only treatment process.

4. Raw Water Desalination

It has been predicted that well before the end of this century a substantial proportion of municipal raw water treatment plants will incorporate, as one of their standard processes, a desalting unit. Some dissolved minerals are just as dangerous, toxic, or lethal as other impurities less difficult to remove. Other minerals are objectionable because of damage they inflict on water pipes, plumbing and fixtures. The technology is at hand for providing the best quality drinking water the residential customer may desire. AWWA's water quality goals will become the minimum quality expected by domestic users of the future because utilities will be able to meet these at a reasonable cost.

Meanwhile, desalination will play a role in correcting quantitative water deficiencies along the sea coasts and where brackish water resources are available, and in upgrading the quality of water supplies where these fall below criteria or standards.

A water utility operator may be faced with a water allocation problem involving several sources. His objective is to meet quantitative and qualitative water supply requirements. If he is concerned only with the over-all concentration of total dissolved solids, a simple method for solving the problem is provided by the type of schedules shown below. In a fictitious example, there are, in addition to the existing water supply, one or more fresh water sources, renovated

wastewater, and an unlimited amount of saline water such as is available on the sea coast. Through the application of distillation to the saline water resource, any desired water quantity and quality can always be achieved regardless of the quality of any source.

Definitions and Symbols

Description	Quantity	Quality
Total water requirements	R	r
Present water supply	S	s
Additional fresh water source I	F1	f1
Additional fresh water source II	F2	f2
Renovated wastewater	W	w
Distilled saline water	D	d

Fictitious Problem

Quantity (mgd)	Quality (ppm)
R = 60; 70; 80	r = 800; 500; 200
S = 40	s = 500
F1 = 24	f1 = 1,200
F2 = 12	f2 = 1,000
W = 30	w = 850
D = infinity	d = 50

Rules are that water is to be used in the order of increasing mineral content; however, distilled water remains last because of cost, and wastewater next to last because of resistance to its use. At this point, costs are otherwise not considered. Nine solutions are grouped below under three schedules:

Schedule I: 60 mgd

	800 ppm			500 ppm			200 ppm		
	mgd	ppm	gpd-TDS	mgd	ppm	gpd-TDS	mgd	ppm	gdp-TDS
R	60x	800=	48,000	60x	500=	30,000	60x	200=	12,000
S	40x	500=	20,000	40x	500=	20,000	20x	500=	10,000
Bal	20		28,000	20		10,000	40		2,000
F2	12x	1,000=	12,000	9x	1,000=	9,000	0		0
Bal	8		16,000	11		1,000	40		2,000
F1	8x	1,200=	9,600	0		0	0		0
Bal	0		6,400	11		1,000	40		2,000
W	0		0	0		0	0		0
Bal	0		6,400	11		1,000	40		2,000
D	0		0	11x	50=	550	40x	50=	2,000
Bal	0		6,400	0		450	0		0
R	60x	693=	41,600	60x	492=	29,550	60x	200=	12,000

Schedule II: 70 mgd

	800 ppm			500 ppm			200 ppm		
	mgd	ppm	gpd-TDS	mgd	ppm	gpd-TDS	mgd	ppm	gpd-TDS
R	70x	800=	56,000	70x	500=	35,000	70x	200=	14,000
S	40x	500=	20,000	40x	500=	20,000	23x	500=	11,500
Bal	30		36,000	30		15,000	47		2,500
F2	12x	1,000=	12,000	12x	1,000=	12,000	0		0
Bal	18		24,000	18		3,000	47		2,500
F1	18x	1,200=	21,600	0		0	0		0
Bal	0		2,400	18		3,000	47		2,500
W	0		0	0		0	0		0
Bal	0		2,400	18		3,000	47		2,500
D	0		0	18x	50=	900	47x	50=	2,350
Bal	0		2,400	0		2,100	0		150
R	70x	765=	53,600	70x	470=	32,900	70x	198=	13,850

Schedule III: 80 mgd

	800 ppm			500 ppm			200 ppm		
	mgd	ppm	gpd-TDS	mgd	ppm	gpd-TDS	mgd	ppm	gpd-TDS
R	80x	800=	64,000	80x	500=	40,000	80x	200=	16,000
S	40x	500=	20,000	40x	500=	20,000	26x	500=	13,000
Bal	40		44,000	40		20,000	54		3,000
F2	12x	1,000=	12,000	12x	1,000=	12,000	0		0
Bal	28		32,000	28		8,000	54		3,000
F1	22x	1,200=	26,400	0		0	0		0
Bal	6		5,600	28		8,000	54		3,000
W	6x	850=	5,100	8x	850=	6,800	0		0
Bal	0		500	20		1,200	54		3,000
D	0		0	20x	50=	1,000	54x	50=	2,700
Bal	0		500	0		200	0		300
R	80x	794=	63,500	80x	497=	39,800	80x	196=	15,700

Note: For the sake of simplicity, whole numbers of millions of gallons per day were used in all three schedules, leaving residues whereby the quality of the blended water is slightly upgraded. In a real situation, this would not be necessary.

The nine alternative requirements have been met, as shown in the following summary:

The Nine Solutions

	800 ppm			500 ppm			200 ppm		
S	40	40	40	40	40	40	20	23	26
F1	8	18	22	--	--	--	--	--	--
F2	12	12	12	9	12	12	--	--	--
W	--	--	6	--	--	8	--	--	--
D	--	--	--	11	18	20	40	47	54
R	60	70	80	60	70	80	60	70	80

The above procedure can be used also if brackish water is available and a single-phase process such as electrodialysis or reverse

osmosis is selected. However, there will be instances where no solution is feasible, because of the limitations of these processes. In those cases, distillation will be necessary. -- In addition to the multiple-source problem as presented here, there is always the possibility of applying some form of desalination to any of the sources directly.

The principal desalination processes are described and discussed in the National Water Commission's report on Desalting (28), and in the annual reports and R & D Progress Reports of the Office of Saline Water, U. S. Department of the Interior. A recent development is the use of selective hollow fibers for removing specific minerals. Cole and Genetelli (29) reported complete carbonate removal as high as several hundred ppm of $CaCO_3$ in the laboratory. DO was reduced 96% from initial saturation. CO_2, ammonia, and low molecular weight organics may also yield to the same process. -- One practical application of selective membranes would be the removal of NaCl from quantities of cheese whey now going to waste. The recovery of desalted whey would provide a nutrient rich in protein and lactose.

Desalting costs have real meaning only if a number of factors are specified. Even with all parameters nailed down, costs are affected by local and temporal opportunities, limitations, and requirements. Only very small desalters are mass produced to fit all local conditions.

The selection of the most suitable desalting process for a given purpose depends on many circumstances. Raw water salinity, hardness,

temperature are but a few. If it is hoped to blend desalted with more raw water for cost reduction, then a process based on a change-of-phase is needed. If desalination is intended for intermittent use, an electric process such as electrodialysis or reverse osmosis permits more flexible operation. If a combined power and desalting plant can be justified, then some form of distillation is the answer. If a relatively small plant with low operating costs is desired to reduce the salt content in brackish water, a membrane process is indicated. A very large plant would probably be designed as a combination of two highly economical distillation processes: multi-stage flash and vertical tube evaporation. The freezing process has applications of its own, and so has ion exchange. Several other processes are theoretically feasible and may some day become practical.

The definitive desalination cost document is the Desalting Handbook for Planners (30), issued in May 1972, jointly by the Bureau of Reclamation and the Office of Saline Water, both in the U. S. Department of the Interior. In this Handbook, the principal cost elements for seven desalting processes are represented graphically by about 50 pages of cost curves, and tabularly by about 25 pages of itemized cost figures. In the tables, costs are organized under capital cost centers and annual cost centers. The standard cost summary form is reproduced below. For each desalting process, the cost summary is preceded by a supporting data sheet and a computation sheet.

COST SUMMARY

PROJECT DESCRIPTION:	PROJECT:
	DATE:
	PRICE LEVEL:

DESALTING PLANT - TYPE: ______ CAPACITY (mgd): ______
ANNUAL PLANT FACTOR (%): ______ INTEREST RATE (%): ______
ANNUAL PRODUCTION (kgal): ______ PLANT LIFE (years): ______
FIXED CHARGE RATE (%, excluding replacement reserve): ______

CAPITAL COSTS

CAPITAL COST CENTERS	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
1. Desalting Plant			
2. Brine Disposal			
3. Water Treatment			
4. Water Intake			
5. Steam Supply			
6. General Site Development			
7. Other			
Subtotal			
8. Interest During Construction			
9. Start-up Costs			
10. Owners General Expense			
Total - Depreciating Capital			
11. Land Costs			
12. Working Capital			
Total - Nondepreciating Capital			
Total Capital Costs			

ANNUAL COSTS

ANNUAL COST CENTERS	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
13. O&M Labor, Supplies, and Maintenance Materials			
14. Chemicals			
15. Fuel			
16. Steam			
17. Electric Power			
18. Other			
Total O&M			
19. Annual Cost - Depreciating Capital			
20. Annual Cost - Nondepreciating Capital			
Total Annual Capital Charges			
21. Annual Replacement Costs			
Total Annual Costs			

COST OF WATER (¢/kgal) ______

GPO 845-614

Total estimated capital, annual, and water costs are extracted below from cost summary sheets for six desalting processes:

Desalination Costs

Item	Unit	Desalting Process*					
		MSF	VTE-MSF	ED	RO	VF-VC	IX
Assumptions							
Days/year	%	90	75	85	90	90	90
Design Capacity	mgd	24.4	58.4	3.2	9.1	1.5	1.5
Interest Rate	%	7	7	7	7	7	7
Plant Life	yr	30	30	30	30	30	30
Annual Charge**	%	8.56	9.06	8.06	8.06	8.46	8.06
Capital Cost	$MM	39.7	54.8	3.34	15.7	3.63	5.7
Annual Costs							
Capital	$MM	3.7	5.0	0.27	1.25	0.31	0.46
O + M	$MM	4.0	5.4	0.36	1.18	0.27	0.25
Total	$MM	7.7	10.4	0.63	2.43	0.58	0.71
Water Cost	¢/Kgal	97	65	63	81	116	141

Source: Desalting Handbook for Planners, by Bureau of Reclamation and Office of Saline Water, U. S. Department of the Interior, May 1972.

* Processes: Multi-stage flash (MSF); Vertical tube evaporation multi-stage flash (VTE-MSF); Electrodialysis (ED); Reverse osmosis (RO); Vaccuum-freeze vapor compression (VF-VC); Ion exchange (IX).

** Annual Charge: This is the percent rate of the capital sufficient to cover the annual interest plus the average annual amortization of the principal. In the case of some processes, the annual charge also includes taxes and insurance: MSF (0.5%), VTE-MSF (1%), and VF-VC (0.4%).

Another table of desalting costs is excerpted from the National Water Commission report (28). It is based on actual experience:

Plant Location	Year	Size (mgd)	Process	Fixed Charge	Water Cost (¢/Kgal)
Buckeye, Ariz.	1962	0.65	ED	6.7%	.69
Key West, Fla.	1966	2.6	MSF	6%	.94
St. Thomas, V. I.	1967	2.5	MSF-dual	6%	.90
Rosarito Beach, Mex.	1969	7.5	MSF-dual	6%	.85

Other cost studies were aimed at conjunctive supply and wastewater desalination. Porter (31) and Mozes (32) conducted such studies, the latter advocating an integrated approach in planning for urban water supply and sewage disposal systems. Wesner and Culp (33) reported on an agreement entered into by Orange County, California, and the Office of Saline Water for the erection of a 15-mgd sea water VTE-MSF distillation plant in conjunction with a wastewater reclamation facility.

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CHAPTER V. TECHNOLOGY AND COST OF WASTE AND RECEIVING-WATER PURIFICATION

Chapter IV was concerned with technology and cost of making raw water fit for use. The present chapter discusses technology and cost of bringing water quality back to normal after use. Since much raw water withdrawn for use has already been used and may be used again, there is a pervading interrelationship between raw and used water resources with regard to their quality and need for treatment. It is nevertheless possible to consider the main problems under separate heads.

Some water purification techniques appear susceptible of application by the Corps of Engineers: By-pass piping of wastes to the ocean, the spatial staggering of outfalls, storm water reuse, collective wastewater treatment and/or desalination, lake water quality management, excess vegetation control, and lagoon construction for various purposes.

A. Wastewater Outfall Management

In this first section, the emphasis is eith[illegible] n interception of effluents for separate conveyance to the ocean, or on economizing (and thus making optimum use of) a stream's waste-assimilative capacity. Individual waste treatment may thereby be completely or largely circumvented. This may be of interest even though pollution control legislation no longer condones it.

1. By-Pass Piping to the Ocean

Pipelines have been sunk into river beds for waste disposal for many years. A stream moves by gravity, and a pipe following its course can inexpensively convey wastes of all descriptions, including sludge, to selected ocean outfalls. Installation and operating costs may not be essentially different from costs of water importation tabulated in Chapter IV, C, 2.

2. Longitudinal Staggering of Outfalls

Two waste disposal methods are available to avoid overtaxing the receiving water's waste-assimilative capacity. The capacity can be stretched by staggering outfalls in space -- or time. The first approach relies on longitudinal spreading of those outfalls which are bunched together in highly populated and industrialized areas, resulting in loads far in excess of the stream's natural self-purification rate. The reoxygenation capacity governs waste loads in tons per mile which the stream can digest. By capturing the outfalls into by-pass pipelines, for release at predetermined distances downstream, it should be possible to protect the quality of the receiving water while reducing the need for additional waste treatment.

The least-cost solution to the Delaware estuary's pollution problem was computed by Graves and Hatfield (1), using treatment at

the source, collective treatment, and longitudinal staggering of municipal and industrial effluents. Mathematical programming resulted in 17 of 44 discharges being treated at the source, and 27 effluents being captured in by-pass piping leading to three collective treatment plants and to downstream staggered releases. The optimization required the use of realistic cost functions for each alternative.

3. Diurnal Staggering of Outfalls

Industrial waste discharges are concentrated between 8 a.m. and 6 p.m.; sewage is produced in two daily peaks. If these loads could be released at staggered intervals throughout the 24 hours of the day, the river could digest them more readily. The construction of 24-hour retention ponds would permit successive rather than simultaneous releases from a number of polluter stations. An appropriate time schedule could minimize by-pass piping and costs.

Conjunctive space and time staggering of discharges can stretch the waste-assimilative capacity of a stream to its maximum. By optimizing between piping costs and storage costs, the most economical waste disposal design can be achieved. Calculations can be made for BOD-type pollution, but also for other water quality parameters such as pH, phosphorus, nitrogen, turbidity, suspended solids, and salinity.

Sobel (2) evaluated alternative time schedules for storing wastes and discharging stored wastes into a water resource. His model related

the capacity of the water storage facility to the desired water quality level. Through application of the Chebyshev criterion, he was enabled to answer two questions: (a) For a given storage capacity, what discharge schedule maximizes the minimum water quality within a given time period? and (b) For a given minimum water quality within a given time period, what is the smallest storage capacity for which there exists a feasible discharge schedule?

B. Wastewater Treatment

Because other federal agencies are charged with responsibility for water pollution control, this section will be brief. Four aspects of wastewater treatment will be reviewed: individual treatment of sewage, storm water, and industrial wastewater; and collective treatment of all such wastes.

1. Sewage Treatment

Sewage can be treated to various levels of purity. To raw sewage can be applied preliminary treatment, primary treatment, secondary treatment, tertiary or advanced waste treatment, and desalination. Secondary waste treatment has traditionally been considered adequate for sewage disposal in a stream or lake. The latest intent of Congress takes issue with that view. Some sort of tertiary treatment will henceforth be required.

a. For Disposal

Treatment processes are selected to purify to predetermined levels of purity the sewage resulting from the disposal of a large variety of domestic and other wastes into a potable public water supply of highly variable quality. Such processes are linked together in groups to perform in succession the mechanical (primary treatment), biological (secondary treatment), and chemical (tertiary treatment) removal of specific types of contaminants. A table of processes, not all of which are necessarily included in every sewage treatment operation, together with their efficiencies in removing pollutants, is presented below:

Processes	Removal in Percent (a)					
	SS	BOD	COD	TKN	P	TDS
Preliminary Treatment						
Screening						
Grinding						
Grit, Grease, and Scum Removal						
Primary Treatment (Mechanical Process)	63	32.5	35.7	16.7	15.4	--
Sedimentation in Settling Basins						
Mechanical Aeration						
Final Sedimentation						
Chlorination or Other Disinfection						
Secondary Treatment (Biological Processes) (b)						
a. Trickling Filter Process		85				
b. Activated Sludge Process	91.3	90	85.7	33.3	23.1	--
Aeration by Air Diffusers						
Sludge Thickening						
Sludge Elutriation						
Vacuum Filtration						
c. Digestion Process		92				
Aerobic Digestion in Stabilization Pond						
Completely Mixed Anaerobic Digestion						
Tertiary Treatment (Chemical Processes) (c)						
a. Microscreening	97.3	96	90	43.3	30.8	--
Rapid Sand Filtration						

Processes	Removal in Percent (a)					
	SS	BOD	COD	TKN	P	TDS
b. Lime Clarification Sequence						
Coagulation						
Flocculation (alum or lime)						
Sedimentation	93.5	98	93.4	50	46.2	--
Ammonia Air-Stripping	93.5	98.5	93.4	886.7	46.2	--
Multi-Media Filtration	98.7	98.5	93.7	86.7	84.6	--
Granular Carbon Adsorption	99.1	99.5	98.6	90	84.6	--
c. Nitrification and Denitrification	97.8	98	94.9	93.3	96.2	--
Multi-Media Filtration	99.6	98	95.1	95	98.5	--
Desalination (d)						
Distillation or Evaporation						10
Freezing						50
Ion Exchange						500
Electrodialysis						500
Reverse Osmosis						200

(a) SS = Suspended solids; BOD = 5-day biochemical oxygen demand; COD = Chemical oxygen demand; TKN = Total Kjeldahl nitrogen, including ammonia and organic nitrogen, but excluding nitrite and nitrate nitrogen; P = phosphorus; TDS = Total dissolved solids.

(b) The three secondary treatment processes are alternate -- not cumulative technologies.

(c) The three tertiary treatment sequences again are separate options which are rarely cumulated.

(d) Effect indicated as residue in ppm of TDS.

Adapted from unpublished data received March 15, 1973 from Robert Smith, National Environmental Research Center, EPA, Cincinnati, Ohio.

Additional treatment processes not listed above include:

Bar screen

Centrifugation of organic sludges

Clarifier for activated sludge process

Comminution (reduction to powder)

Flotation (agitation with water, oils and chemicals causing differential wetting, the unwetted particles being carried by air bubbles to the surface for collection)

Incineration of sludges

Recarbonation with carbon dioxide (for granular carbon adsorption process)

Several authors described biological treatment processes involving wastewater lagoons and stabilization ponds. Amin and Ganapati (4) distinguished between the bacterial (no DO but many protozoa) and the algal phase (abundant DO) of lagoons; they noted no appreciable sludge formation. Kormanik (5) discussed the conjunctive operation of two artificially aerated lagoons, one keeping solids in suspension, the other allowing them to settle. The combination reduces BOD removal time to a minimum. Canter and Englande (6) reviewed State regulations and criteria for designing stabilization ponds.

The City of Cleveland is in the process of replacing its inadequate sewage treatment plant with a new, completely anaerobic, physical-chemical treatment facility of 100 mgd capacity. According to an

anonymous article in Environmental Science and Technology (3), this will be the largest plant of its type in the world. The same process will be used, in Virginia, by the City of Alexandria, and the Counties of Arlington and Prince William; and, in California, by the City of Los Angeles. The Cleveland plant, which will receive about 50% of its input, by volume, from industry, will remove 93% of suspended solids, 90% of BOD and phosphorus, and will minimize the effects of toxic materials and heavy metals. It will make use of the following processes: Comminution, the aerated grit chamber process, addition of lime slurry, chemical flash mixing, addition of polymer slurry, flocculation-clarification, addition of CO_2, recarbonation in a basin, addition of more polymer slurry, horizontal pressure filtration, activated carbon column processing, and chlorine disinfection. The effluent will be discharged to Lake Erie.

The effectiveness and cost of various sewage treatment processes has been tabulated at EPA's National Environmental Research Center. Eilers (7) listed individual processes and common chains of processes, as follows:

Wastewater Disposal Treatment Costs

Treatment Process	Treatment Cost (¢/Kgal) 1 mgd	10 mgd	100 mgd
1. Primary Sedimentation + Sludge Disposal	13.7	7.7	4.4
2. Primary, Activated Sludge, + Sludge Disposal	23.3	13.5	8.2
3. Microscreening	1.4	1.1	0.9
4. Single-Stage Lime Clarification	17.1	6.9	3.7
5. Two-Stage Lime Clarification	20.9	8.4	5.0
6. Ammonia Stripping and Recarbonation	7.0	4.0	3.0
7. Multi-Media Filtration	6.8	3.0	1.4
8. Granular Carbon Adsorption (40-min contact)	32.3	10.8	7.2
9. Chlorination (8 mg/1)	2.1	0.8	0.4

Inasmuch as the above costs contain some duplication (items 1 and 2, 4 and 5), they are not all additive. Chains of processes which lead to specified degrees of contaminant removal follow:

Treatment Effectiveness and Costs

Estimated Contaminant Removal, in Percent				Processes	Treatment Cost (¢/Kgal)		
BOD	COD	Phos	Nitr	Included	1 mgd	10 mgd	100 mgd
35	--	10	0	1	13.7	7.7	4.4
88	--	25	0	2,9	25.4	14.3	8.6
95	--	35	0	2,3,9	26.8	15.4	9.5
97	--	92	0	2,4,9	42.5	21.2	12.3
97	--	92	0	2,5,9	46.3	22.7	13.6
97	--	92	85	2,4,6,9	49.5	25.2	15.3
--	98	95	85	2,4,6,7,8,9	88.6	39.0	23.9
--	98	98	85	2,5,6,7,8,9	92.4	40.5	25.2

Note: Costs in the above two tables are as of Jan. 1970.

b. For Reuse

If renovated wastewater is to be reused for public water supply, a very complete succession of sewage treatment processes must be applied. Desalination is advised, not that the last vestige of mineral content needs to be removed, but in order to minimize the risk of harm from virus, pathogens, toxic or radioactive substances.

But treated wastewater can be utilized in many ways short of domestic water supply. An ingenious method of reuse whereby much of the treatment is made unnecessary has been named the cascade method of water reuse. Water whose quality no longer meets the requirements of one use can be of value in another use with less stringent quality specifications; and this process can be repeated several times before a single treatment for disposal is performed.

"Some Notes on Reuse" was the title of an article by Suhr (9). He recalled the Chanute story of 1956, when the same water was recycled about seven times during a five-month period in drought-stricken Kansas. The city of Windhoek, South-West Africa. installed in 1968 a wastewater reclamation plant for permanent reuse purposes.

The most notable recycling plant in the U. S. is at Lake Tahoe, California. In operation 24 hours a day since 1968 with a capacity of 7.5 mgd, it produces water exceeding all drinking water standards. Removal efficiency for selected contaminants is: Suspended solids, color, odor, coliform bacteria, and viruses (100%); turbidity (99.9%), BOD (99.4%); phosphorus (99.1%); MBAS (97.9%); and COD (96.4%). Costs were tabulated by Evans and Wilson (14) as follows:

Lake Tahoe's Wastewater Treatment Costs
(Plant Capacity: 7.5 mgd)

Process	Capital Cost (¢/Kgal)	M + O Cost (¢/Kgal)	Total Cost (¢/Kgal)
Conventional Tmt	6.75	10.45	17.20
Advanced Waste Tmt			
Lime Coagulation	0.97	3.13	4.10
Lime-Mud Dewatering	0.29	0.65	0.94
Lime-Mud Recalcining	1.06	3.21	4.27
Ammonia Stripping (intermittent)	0.80	0.71	1.51
Recarbonation	0.40	0.44	0.84
Filtration	1.78	2.33	4.11
Carbon Adsorption	1.63	1.12	2.75
Carbon Regeneration	0.52	2.17	2.69
Total AWT	7.45	13.76	21.21
Miscellaneous	0	1.16	1.16
Grand Total	14.20	25.37	39.57

Denver, adds Suhr, is known to operate a most progressive water utility. Its engineering achievements include the H. D. Roberts Tunnel (1962), which, 23.2 miles in length, is the world's largest water tunnel. A 100-mgd wastewater reclamation system is proposed for completion in 1985; a large portion of Denver's waste is to be recycled for domestic use. Two demonstration plants, say Linstedt, Miller and Bennett (10) are part of the project. The motto is "Successive water use" -- not true cascading reuse because some intermediate treatment is performed. Linstedt, Bennett and Work (11) determined the intermediate treatment requirements.

An excellent dissertation on wastewater renovation was contributed by James F. Johnson (12), now a staff member in the Office of the Army's Chief of Engineers. From one of his tables are transcribed the following water reuse data:

Incremental Utility of Treated Sewage Effluent

Treatment Process	Application				
	Irrigation	Recreation	Recharge	Industry	Domestic
Primary-Secondary	Non-food crops	--	--	--	--
Coagulation-Sedimentation	General	Non-body-contact	Short-term	Low quality	--
Carbon Adsorption	High quality	Body-contact	Long-term	Good quality	--
Electrodialysis			Indefinite	High quality	--
Disinfection					Potable

A. Wolman (39) told the story of the Bethlehem Steel Company's predicament when its underground water source began to deplete in 1941. The company needed cooling water with a minimum safe yield of 50 mgd, for use in its steel plant at Sparrow's Point, Md. An elegant solution was found through the cooperation of the City of Baltimore with the steel company. The treated effluent of the Back River Sewage Treatment Works of Baltimore City had a continuing yield of 90 to 100 mgd and could be delivered very economically for industrial use. The company agreed to pay all costs attendant upon processing, pumping, delivering, and distributing the effluent from the Back River plant. The capital expenditure was somewhat in excess of $2 million. One unexpected problem was the chloride content of the sewage; some of the sources of chlorine have since been eliminated.

The Santee County (California) Water District (13) completed in 1968 the construction of an activated sludge sewage treatment plant operated in conjunction with an oxidation pond and spreading basins. The effluent, filtered through natural underground aquifers, emerges into the recreational lake system. From the lake, the water is distributed for reuse in recreational, agricultural, and industrial applications.

Smith (8) developed costs of wastewater treatment where the object is reuse as agricultural, industrial, recreational, and even potable water:

Wastewater Reuse Treatment Costs

	Treatment Process	Treatment Cost (cents/Kgal) 1 mgd	10 mgd	100 mgd
1.	Conventional Treatment	36.0	11.5	6.3
2.	Separate Nitrification	11.5	4.0	2.0
3.	Lime Clarification	11.2	8.4	5.0
4.	Filtration	6.8	3.0	1.4
5.	Carbon Adsorption	32.3	10.8	7.2
6.	Ion Exchange	22.9	16.1	10.9
7.	Electrodialysis	26.7	17.0	11.2
8.	Reverse Osmosis	37.8	30.4	27.6
9.	Chlorination	2.3	0.9	0.3
10.	Brine Disposal (Evaporation Ponds)	7.8	7.0	6.2

The following chains of processes achieve water renovation levels suitable for various types of water reuse:

Reuse Treatment Effectiveness and Costs

Effluent Concentration (mg/l) COD	Phos	Nitr	TDS	Processes Included	Suitable Reuse	Treatment Cost (cents/Kgal) 1 mgd	10 mgd	100 mgd
50	10	20	1000	1	--	0	0	0
30	8	19	1000	1,4,9	Agricultural	9.1	3.9	1.7
22	0.2	18	1000	1,3,4,9	Industrial	20.3	12.3	6.7
22	0.2	15	1000	1,2,3,4,9	Recreational	31.8	16.3	8.7
5	0.2	8	500	1,2,3,4,5,6,9	Potable	87.0	43.2	26.8
5	0.5	5	200	1,4,8,9	Potable	46.9	34.3	29.3
10	8	18	1000	1,5,9	Potable	35.4	11.7	7.5

The above costs do not include the cost of conventional treatment or the cost of brine disposal. Costs are as of January 1970.

Koenig and Ford (15) determined under what conditions wastewater reuse is cheaper than disposal, and established the following general relationships: Wastewater disposal by land spraying is cheaper than any reuse. Disposal is also cheaper than reuse when renovation requires distillation or deionization from 2500 ppm of TDS. But wastewater reuse is cheaper than disposal when:

a. Wastewater contains valuable products.
b. Incremental water supply costs over $5/Kgal.
c. Effluents are strictly regulated.
d. Effluent quality must be higher than raw water quality.
e. Disposal involves injection into mined cavities.
f. Renovation requires only standard secondary treatment and disposal is done by injection or 5-mile transport.
g. Renovation requires distillation or deionization from 2500 ppm, and disposal is done by injection or by 50-mile transport of wastes weaker than 1500 ppm.

---

2. Storm Water Treatment

Storm water may carry higher pollutant loads than sewage. If it enters the sewer system, it may overtax the treatment plant's capacity, necessitating the by-pass of sewage along with storm water. Combined sewers are not believed effective in controlling pollution. A more satisfactory design would consist of separate sewage and storm water collection systems, with the option of routing storm water through the treatment plant when the latter's capacity is adequate, and an automatic by-pass provision for storm water only, whenever that capacity comes close to being exceeded. Settling ponds may have the

advantage of cutting down the excessive turbidity if not the contaminants. And if such ponds are located upstream from the sewage treatment plant, they might act as temporary buffers permitting subsequent purification of the storm water in the treatment plant.

Storm water needs attention, whether it is intended for disposal or for reuse. Not only is it sudden, hard to contain, sometimes disastrous, but may likely be toxic, containing lead and oil in solution, and may require expensive desalting treatment.

Angino, Magnuson and Stewart (16) analyzed the quality of storm water with a view to its reuse. They found in it as much as 5,500 ppm of lead, 2,150 ppm of chloride, 34 ppm of COD, 27 ppm of hexavalent chromium, 5 ppm of bromine, and a relatively high content of nitrate.

E. L. Johnson (17) estimated the cost of separate storm water collection and treatment in the U. S. at $49 billion -- over ten times the cost of industrial waste treatment. Partial separation of storm water from sewage would cost $30 billion. The use of holding ponds and underground reservoirs, if practicable everywhere, would cost $12 billion.

3. Industrial Wastewater Treatment

a. For Disposal

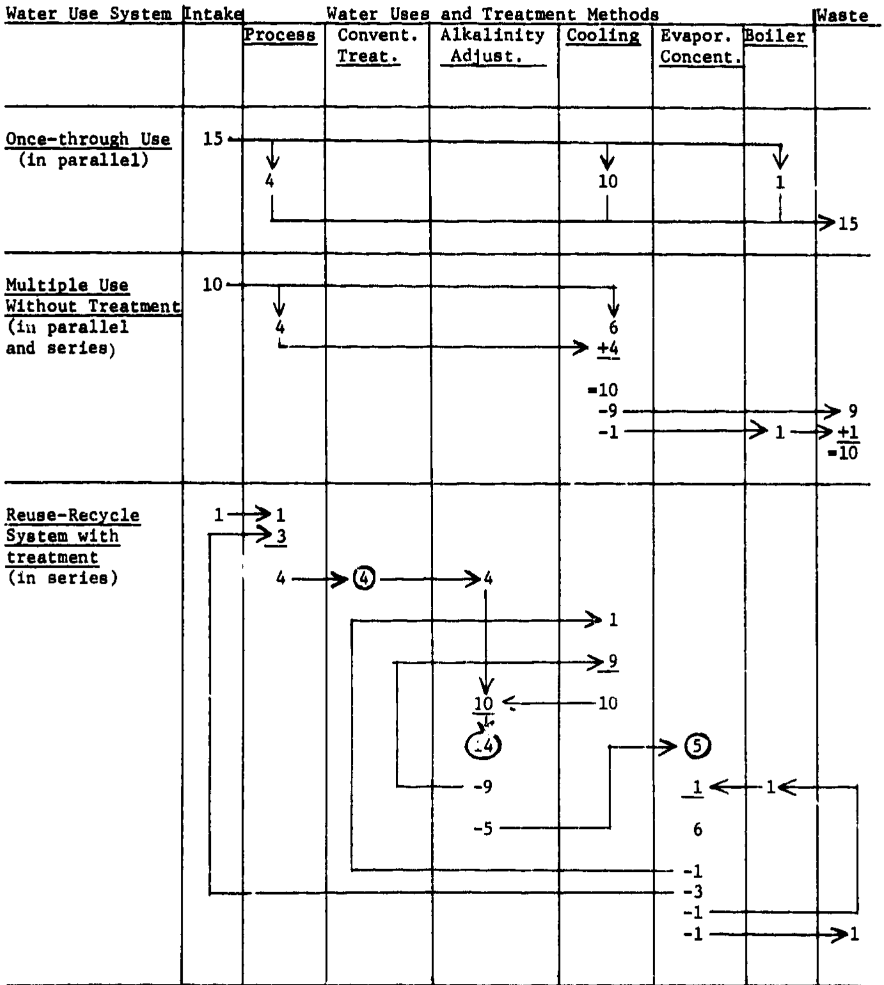
All of American industry is facing the need for cleaning its wastes, or modifying its processing methods so as to reduce wastewater volume and/or concentration. Bramer (18) investigated the steel industry, the highest user of water: 40,000 gal per ton of finished steel. Nine processes generate pollution, and more efficient steel production facilities have increased the potential pollution. Where water is scarce, or where pollution restrictions are in effect, large steel mills have reduced wastewater effluents to as little as 1000 gal per ingot ton. This can only be achieved through recycling. Recycling involves treatment, and wherever treatment for disposal restores water to a quality fit for reuse, why discharge it? Thus, it will become increasingly more difficult to draw a line between treatment for disposal and treatment for reuse.

b. For Reuse

Rey, Lacy, and Cywin (44) studied the possibilities of industrial wastewater reuse as a means of pollution abatement. Process water, seldom recirculated, offers excellent opportunities for reuse. To reduce wastewater discharge volume, it is necessary either to recycle increasing amounts of spent water within each function, or to reuse

spent water from one function as makeup water for another. Three methods of industrial water use were described in diagram form. They are summarized below in a single figure. Each method provides 4 units of process water, 10 units of cooling water, and 1 unit of steam make-up water. In the once-through method, 15 units of water are withdrawn and released; in the multiple-use system, the same functions are performed by 10 units; the reuse-recycle method, incorporating several treatment processes, is capable of providing the same services with a single unit. With this last method, conventional treatment, alkalinity adjustment, and evaporation concentration (the latter applied to one-third of the water), furnish pure water to the boiler and for disposal, 75% pure and 25% intake water for processing, and 10% pure and 90% partially treated water for cooling.

Industrial Water Use Systems
(Numbers represent water units)



Note: A circle indicates quantity treated.

The same authors tabulated industrial wastewater treatment costs applicable to the removal of main pollutant types:

Industrial Wastewater Treatment Costs (1971)

Pollutant	Treatment Process	Removal (ppm)	Cost per Kgal (¢)	Cost per lb Removed (¢) Pollutant	Sludge	Total
Suspended Solids	Primary: Sedimentation	200	2.5	2.0	0.5	2.5
Organic Matter	Secondary: Biological Oxidation	400	5.0	2.0	1.0	3.0
TDS incl. Hardness	Multi-effect Distillation	3500	100.0	3.5	-	3.5
	+ Evap. Pond (1 mgd)	250	-	-	-	-
Alkalinity (as $CACO_3$)	Acid Addition (a)	-	-	2.0	-	2.0
	Total:		107.5	9.5	1.5	11.0

(a) Total cost at twice the chemical cost of 1 cent/lb for sulfuric acid.

c. For By-Product Recovery

Industrial wastewater reclamation may pay a bonus: the recovery of materials, chemicals, or by-products formerly discharged in the effluent. The recovered products need to be transformed into marketable form.

Reporting on a study sponsored by the Office of Saline Water, Bovet (19) listed six industries which can profitably treat their effluents through desalination because of the commercial value of the recovered by-products. By desalting residual whey traditionally discharged into streams by the cheese industry, a food product rich in protein and lactose can be recovered at the rate of $300 million per year and at a desalting cost of $120 million per year. Through the use of ion exchange or electrodialysis, the plating and metal finishing industry can recover valuable chemicals such as chromic acid, nickel sulfate, and cyanides of copper, zinc, brass, cadmium, and silver. These are highly toxic when released to streams or lakes. The pulp and paper, iron and steel, nuclear power, and coal mining industries can likewise benefit from by-product recovery through desalination.

4. Collective Treatment

This consists of the interception of effluents before their release to receiving waters, and their conveyance by pipeline to a

conveniently located plant site for aggregate treatment and disposal. The treatment may involve conventional methods (including tertiary treatment), desalination, or both.

Combined treatment, wrote Eckenfelder and Adams (20), may have certain unexpected advantages. Many industrial wastewaters are deficient in nitrogen and phosphorus, while these nutrients are usually excessive in municipal sewage. Thus, municipal and industrial effluents may be partly compensatory. Cost dictates in most instances what effluents should participate in collective treatment. Conveyance costs must be weighed against economies of scale. Certain pretreatment may be required or desired. The organic content of municipal and industrial wastes responds to different treatment processes; completely mixed activated sludge or aerated lagoon systems, operated with single or multi-stage aeration basins, appear most amenable to combined biological treatment.

Factors which significantly influence the cost of collective wastewater treatment are: the flow rate (affects the size of all processing units, therefore capital cost), BOD concentration (affects the size of the aeration basin, aeration HP required, and biological sludge handling facilities), suspended solids (affect over-all sludge handling facilities), and biological reaction rate. The authors tabulated treatment process sizing factors and collective treatment costs as follows:

Capacity Sizing Factors for Individual Processes in Collective Wastewater Treatment Facilities

Range of Flow Rate (Q) = 1 - 100 mgd

Process	Sizing Factor
Preliminary	1.0
Primary clarification	2.0 - 0.008Q
Activated Sludge	1.3 - 0.002Q
Aeration	1.8 - 0.004Q
Sludge return	2.0 - 0.005Q
Final clarifier	2.0 - 0.007Q
Chlorinator	1.0
Thickener	1.5 - 0.004Q
Aerobic digester	1.5 - 0.003Q
Anaerobic digester	2.0 - 0.005Q
Centrifuge	2.0 - 0.005Q
Vaccuum filter	2.0 - 0.005Q
Sludge drying beds	1.0

Capital and Operating Costs of Collective Wastewater Treatment Facilities

(Costs as of September 1969)

Process	Sizing	Cost Base	Capital Cost ($1000)	Operating Cost ($/mgd)
Pretreatment	Q	Q	$19 \times Q^{0.63}$	$500 + \frac{2,150}{Q^{0.63}}$
Primary clarification or sedimentation	Overflow rate (800 gal/sq ft/day)	SA	$17.3\ SA + 6.7\ (SA)^{0.1}$	$909 + \frac{2,370}{Q^{0.5}}$
Activated sludge	F/M ratio nitrification rate, or reaction rate	Basin volume (mg)	(226 x volume) + 67	$2,700 + \left(\frac{2,500}{volume}\right)^{0.67*}$
Oxygen requirements	BOD reduction and respiration	Aerator HP	--	--
Blower house	-	-	$13.6 + \frac{7.6\ cu\ ft/min}{1,000}$	--
Sludge pumps	Q	Q	4.7 + 1.45Q	--
Final clarifier	Overflow rate (750 gal/sq ft/day)	SA	$16.2\ SA + \frac{6.9}{SA^{0.13}}$	--
Aerobic digester	15-day retention time	Basin volume (mg)	--	--

Capital and Operating Costs of Collective Wastewater Treatment Facilities (Cont'd)

Process	Sizing	Cost Base	Capital Cost ($1000)	Operating Cost ($/mgd)
Anaerobic digester	20-day sludge retention	Volume (1000 cu ft)	$134V + \frac{13.8V}{V^{0.87}}$	$\frac{1200V}{Q}(0.048 + \frac{0.54}{V^{0.5}})$**
Thickener	Mass loading (10 lb/sq ft/day)	SA	$SA(24.2 + (\frac{11.7SA}{13.3\ \exp})$	--
Centrifuge	Flow rate (gm/HP)	HP	--	--
Vaccuum filter	4 - 7 lb sludge/day/sq ft	Area (sq ft)	$16.5 + 48\ \frac{Area}{100}$	$0.18\frac{S}{Q}(\frac{700}{F} + 0.38\ (2-0.1Q) + 0.027\frac{C}{F})$
Sludge drying beds	0.0165 lb sludge/day/sq ft	Area (sq ft)	--	$1.2\frac{S}{Q}(0.21 + \frac{29.7}{S^{0.5}})$
Sludge incinerator	Solids/day (lbs)	Solids/day (lbs)	$\frac{S}{24,000}(170) + 7.15S^{0.61}$	$1500 + \frac{6,450}{Q^{0.63}}$
Chlorinator	Q	Q	$11.6 \times Q^{0.47}$	--
Tertiary treatment	Q	Q	--	--
Control house	-	-	$51.6 \times Q^{0.7}$	--

Legend: C = Capital costs
F = Vaccuum filter area (100 sq ft)
Q = Flow rate (mgd)
S = Total sludge production (lb/day)
SA = Surface area (1000 sq ft)
V = Volume (mgd or 1000 cu ft, see Cost Base)

* = Includes final clarifier, sludge return blower; excludes power cost.
** = Includes thickener and cludge handling.

From an unpublished study entitled "Economics of Consolidating Sewage Treatment Plants by Means of Interceptor Sewers and Force Mains," by Smith (21), is borrowed the formula for calculating the break-even distance between two communities beyond which a joint treatment plant is no longer economical. The formula reads:

$$L = \frac{T_c + T_r - T_{cr}}{Q_c \times C_s(Q_c)}$$, where

L = Break-even pipeline length

T_c = total cost of treatment at contributor community

T_r = total cost of treatment at the receiving community

T_{cr} = total cost of treatment in combined plant

Q_c = volume flow from contributing community (mgd)

C_s = total cost of gravity sewers (cents/Kgal/mile)

$C_s(Q_c)$ = total cost of gravity sewer at the average flow Q_c.

The corresponding equation for force mains is written as follows:

$$L = \frac{T_c + T_r - T_{cr} - Q_c \ C_{ps}(Q_c)}{Q_c \ C_{fm}(Q_c)} \text{, where}$$

C_{ps} = total cost of pump stations for force mains (cents/Kgal)

$C_{ps}(Q_c)$ = total cost of pump stations for force mains at the average flow Q_c

C_{fm} = total cost of force mains (cents/Kgal/mile).

In the most optimistic case, the length of pipeline which is economically feasible seldom exceeds 10 miles.

C. Other Liquid Waste Control

1. Land Disposal

This technique is familiar to the Corps of Engineers as an inexpensive and advantageous means of disposing of sewage while improving soil fertility. It has been used for generations in Europe and has proved its value. The same method can be used for sludge disposal, but sludge can be made more easily assimilable to the soil by mixing with sewage. In that form, liquid wastes serve two purposes: irrigation and fertilization. Among major problems is acceptance of the land spraying practice by farmers and land owners.

Municipal Sewage Effluent for Irrigation was the title of a Symposium (40) held in Louisiana in 1968. Papers covered water pollution effects, soil effects, crop response, health, economics, and legal considerations. Municipal sewage effluents are a valuable resource, said the authors,

that could be used to irrigate and fertilize large acreages of land. This would simultaneously avoid releasing too high a concentration of nutrients to the streams and lakes, and thereby producing excessive algal growths. Municipal wastewaters are used for land spraying in a few Western communities, where water supplies are scarce.

Could it be that farmers resist land spraying because of the uncertainties involved? When they irrigate with clear water and fertilize with known chemicals at precise rates per acre, they may be better able to control the crops they plant or sow.

Bendixen et al (41) discussed the relative merits of three methods of liquid waste application on land. Wastewater is applied equally well by flood irrigation (splash plate), spray irrigation (nozzle), and ridge and furrow irrigation (distribution line). The latter system has longer equipment life before remedial measures are required.

An editorial writer of the Journal, Water Pollution Control Federation (42) displayed a degree of impatience with those who advocate land disposal of wastewater as THE answer to water pollution problems. He stated that the Journal, WPCF, described such a land disposal project in its Vol. 1, No. 1, dated October 1928, and in many subsequent articles. This idea, therefore, is not new. Some of the technical and economic problems inherent in land disposal of wastewater are: Soil characteristics, build-up of salts and heavy metals, odor problems, land availability and cost,

initial system cost and amortization, ultimate effects on groundwater quality and receiving streams.

Cantrell et al (43) made a feasibility study of municipal sewage use for irrigation. Sprinkler irrigation using wastewater is safe for field crops and pasture but is not recommended for fruits and vegetables. The cost of using sewage effluents compares favorably with costs of other water sources. In the area around Ruston, Louisiana, average annual cost of wastewater irrigation was $54.82 per acre, compared with $105.87 per acre for well water. This did not take into account the fertilizer value of the effluent, which was about $17.50 per acre-foot, or the savings of sewage treatment costs.

2. Industrial Process Modification

Many traditional manufacturing processes were inherited from days of plentiful water supplies and modest industrial activity. Industrial expansion has changed all this. It is time to take another look at industrial processes from the standpoint of their quantitative water requirements and qualitative effects on wastewater effluents.

Boiler make-up water is too valuable to discard, and is therefore usually recycled. -- Process water is different: certain industrial processes are highly wasteful of water supply, and/or may generate high pollution loads, sometimes of a type that resists treatment. Industrial process

redesign may hold good promise of avoiding or reducing these evils. -- Product water is scarcely subject to waste or discard. -- Cooling water is discussed below under Subsection 5. -- Sanitary and firefighting water constitutes a minor proportion of the industrial water supply, and raises no specific problems.

Löf and Kneese (22) surveyed the sugar beet industry with a view to disclose opportunities for process modification. Firms subject to a waste disposal charge have led the campaign for modifying their processes and increasing the degree of water recycling. -- Other opportunities exist and will be exploited as industrial pollution control regulations take effect.

In a study sponsored by the Institute for Water Resources of the Corps of Engineers, the National Bureau of Economic Research (45) surveyed Changing Water Use in Selected Manufacturing Industries. Chapter 5 of that study reviews technical changes in the steel industry, the pulp and paper industry, in petroleum refining, the chemical industry, and the primary aluminum industry in response to water supply and wastewater disposal cost increases. Three conclusions are: the possibilities for changes in the use of cooling water are substantially greater than in the use of processing water. The impact of various proposed technologies on water use is rarely discussed even in the high water using industries. And finally, technical changes unrelated to an industry or its use of water

may well have a greater impact on it than its adaptation to changes in water requirements, water cost, and waste disposal cost.

3. River Bed and Lake Purification

Occasional suggestions have been found in the literature to the effect that dredging of excess sediment and anaerobic sludge from the bottoms of streams and lakes may be beneficial. Sediment accumulations can cause trouble to navigation channels, water intakes and other installations along waterways. Sludge and benthic biomasses rob the water of DO. Periodic dredging may check these ills while reducing anaerobic conditions and turbidity. The extent to which sediment and sludge dredging is economically justified has not been established.

Lakes and impoundments have additional problems due to their stagnant characteristic. They are subject to cumulative pollution. A number of measures can be taken to arrest and hopefully reverse that trend. Control of excessive vegetation is discussed in Subsection 4. Lake water aeration is feasible, as recorded in Chapter IV, A, 2, either through continual diffused air bubble release, or intermittent mechanical surface aeration during lake destratification (23). Wastewater outfalls are henceforth due for treatment. This leaves diffuse discharges, most of which are natural and escape control.

Northwestern University (24) advocated the construction of a barrier across the southern end of Lake Michigan to isolate the concentrated waste discharge area from the water supply and beach areas. -- The mandatory change-over to approved types of marine sanitary facilities aboard 30,000 pleasure craft in Michigan lakes has been ordained.

Cost figures for lake purification were not found in the recent literature.

4. Excess Vegetation Control

The controversy over the causes of excessive algal and other vegetable growths in lakes and streams was reported in Chapter I, B, 2. It appears evident that comprehensive measures are called for. Phosphorus and nitrate should be removed from sewage unless, as suggested in Subsection B, 4 of the present chapter, an acceptable balance of these nutrients can be

achieved by combining municipal and industrial wastes. All other types of nutrients, such as carbohydrates, humus, BOD, and other organic matter should likewise be removed from effluents.

Levin et al (27) tested the activated sludge and biological sludge process of phosphorus removal, which was found capable of removing 90% of total phosphorus in raw municipal waste. It promises to be significantly cheaper than other treatment processes. Reeves (28) narrowed down possible processes for nitrogen removal to three most feasible ones: air stripping of ammonia, ion exchange, and biological nitrification and denitrification.

Lakes and streams threatened with hypertrophication could be stocked with herbivorous fish. The European carp, which has made a pest of itself, and the Chinese amur, which has been used successfully in closed ponds in Arkansas, are the only species available for this service.

Effective algal bloom control through application of copper sulfate was discussed by Young and Lisk (25). This has been confirmed by other sources, as noted in Chapter IV, C, 3. A concentration of 2 ppm of copper sulfate is suggested in the literature. Frost (29) advocated the application of copper sulfate to a depth of ten feet to control algal growths in Penacook Lake, a 3,380 acre-feet supply for the City of Concord, N.H. This would cost the city of 30,000 the modest sum of $340.

Oskam (26) investigated artificially generated turbidity as a means of algal growth control, on the theory that growth is the balance between photosynthesis and respiration. By reducing light penetration, growth may be checked.

Once the inflows are under control, it may be advisable to proceed to a one-time massive harvesting of algal blooms and other excessive growths.

Phreatophytes are more difficult to eradicate. Their roots penetrate to 100-foot depths.

5. Thermal Pollution Control

The exponentially growing demand for electric power is an inexorable reality. Four possible answers to the problem of thermal discharges from fossil or nuclear power plants follow:

1. Excess heat is viewed as a resource. In northern latitudes, heat could be used in winter to keep waterways and harbors open to navigation, and in summer to irrigate tropical fruit. Entire communities could be heated and air conditioned. Sea water can be desalted on ocean coasts with spent steam as it leaves the power plant turbine.

2. The heated water is discharged to receiving waters. This appears as the least stable answer for future years.

3. Lagoons or cooling ponds buffer the temperature rise in the receiving water after a period of detention. A cooling pond lends itself to partial or total recycling, thus expanding the number of feasible power plant sites.

4. Cooling towers bring down water temperature to levels acceptable for disposal, and also permit cooling water recycling. They open up a number of additional power plant sites. -- Both ponds and towers warm up the air; too many of them could alter the climate.

Winiarski and Tichenor (30) described cooling towers and their performance. Sixteen permutations of cooling tower types are feasible: counterflow vs. crossflow, dry vs. wet, splash packing vs. film packing, and fanned airflow vs. natural draft towers. Large wet natural draft cooling towers, claim the authors, have been used in Europe for over 50 years. They are large chimneys shaped to pull a draft of air over a large water surface. A mathematical model of such towers was developed by the authors.

A very complete discussion of heat dissipation by once-through, supplemental, and closed-loop cooling may be found in a report by the Committee on Power Plant Siting of the U. S. National Academy of Engineering (31). Three cost tables are excerpted from this report and from the monograph on thermal pollution by Parker and Krenkel (32).

Dollar Costs per KW in Water Cooling Devices

Cooling Device	Capital Cost ($/KW) Source 1	Source 2	Source 3
Run of river cooling	5	1.0	-
Bay or lake cooling	6	3.5	-
Cooling pond	10	-	-
Cooling Towers			
Wet induced draft	-	3.2	7
Dry induced draft	-	-	27
Wet natural draft	7.5 - 11	7.2	11
Dry natural draft	22	-	25

Note: Plant sizes are 1,800 MW (Source 1), and 150 MW (Source 2); no size was given by Source 3.

Estimated Number of Cooling Towers in the U. S. and Aggregate Investment to Year 2000

Cooling Tower	Est. Number of Towers	Aggregate Investment ($ billion)
Wet induced draft	380	11
Dry induced draft	0	--
Wet natural draft	540	16
Dry natural draft	1,880	60
Total:	2,800	87

Capital and operating costs for individual units of the above types of cooling towers are as follows:

Capital and Operating Costs per Cooling Tower Unit

Cooling Tower	Capital Cost ($1000)	Annual Cost ($1000)
Wet induced draft	28,715	6,453
Dry induced draft	32,305	7,283
Wet natural draft	29,580	6,476
Dry natural draft	31,905	7,217

Note: The above costs are for cooling towers serving a 200 MWe power plant.

Löf and Ward (33) estimated the additional cost of recirculation cooling as 2-3% of the total cost of electricity generation and distribution. Ward (34) later amended this estimate downward to 1%.

6. Radioactivity Control

Discounting the effects of natural radioactivity (minimal) and nuclear explosion fall-out, as well as the continuous threat of massive nuclear reactor leaks, the main danger of radiation is that emitted by radioactive substances discharged to streams and lakes. These may

penetrate the human body through the food chain. Micro-organisms ingesting radioactive particles deposited in river and lake sediment are in turn swallowed by larger biota. Shellfish and fish who feed on these pass on the particles to man. Human health can be safeguarded against this insidious danger by two approaches:

1. Tighter controls in nuclear reactors to eliminate the possibility of leaks;

2. Water treatment for radioactivity removal.

The National Academy of Engineering power plant report (35), already cited in connection with thermal pollution, contains a complete investigation into environmental protection against nuclear radiation. It evaluates current radiation standards. It discusses radioactive waste generation and disposal, equipment drains, floor drains, laundry drains, and the equipment used for removing radioactivity. The transfer of isotopes through the food chain, and concentrations in fish, mollusks and crustacea are also discussed. Radionuclides discharged with cooling water are measured. Treatment of radioactive wastes is another topic.

The definitive answer to all such problems is the development of so-called "clean" reactors; this will hopefully come to pass before the end of the century.

D. Waste Control Cost Allocation

How should public wastewater treatment costs be apportioned among water users? The allocation should be governed by three considerations: the responsibility for disposing of wastes, the wastewater service provided, and benefits received by various groups within society. Two publications addressing this topic proposed fifteen cost-allocation formulas.

J. A. Johnson (36) listed nine methods. With the Public Utility Formula, wastewater disposal service is billed just as water service. Under the Diffused Benefits Formula costs are paid out of general tax levies. The Historic Formula perpetuates existing arrangements. The Added Expenditure Formula allocates storm water treatment costs to property owners first, incremental sewage treatment costs to water users next; or vice-versa. The Alternative Revenue Formula apportions costs to waste dischargers. The Capital-and-Operating-Cost Formula allocates capital costs to property owners, O + M costs to dischargers. The Differential Benefit Formula proportions charges to benefits measured by alternative methods of waste disposal. The Relative-Use Formula charges property owners for storm water, users for sewage. The Joint Committee Formula involves allocation, by representatives of eight national organizations, of itemized costs to property owners (storm water) and users (sewage).

The author estimated the relative cost allocation to users, property owners, and the general public, under each formula as follows:

Wastewater Treatment Cost Allocation
Under Each Formula

Allocation Formula	Cost Allocation in Percent		
	User	Property Owner	General Public
1. Public Utility	100	--	--
2. Diffused Benefits	--	--	100
3. Historical	51	25	24
4. Added Expense	57-67	33-43	--
5. Alternative Revenue	60	27	13
6. Capital + Oper. Costs	40	60	--
7. Differential Benefit	30	50	20
8. Relative Use	74	26	--
9. Joint Committee	45	55	--

Game theory was utilized by Giglio and Wrightington (37) to develop additional alternatives involving free participation in collective facilities. The Measure-of-Pollution Method allocates costs in direct proportion to pollution generated. The Rebate Proportional to Pollution Method is based on allocation of savings among participants. The Alternative Cost Method charges each polluter with the cost differential of operating the collective facility with or without him. The Free Market Bargaining Method lets each participant decide whether to accept the savings of collective over individual waste treatment. The Bargaining-with-the-Regional-Authority Method consists of including the regional

authority as a participant. After receiving the cost of individual treatment, the authority refunds the savings of collective processing.

-- For small numbers of pollutants, method 2 or 3, for larger numbers, method 5 is indicated.

The formula used by New York City for industrial customers was reported by Environmental Science and Technology (38):

D = CFV ((SS-350) + (BOD-300)), where

D = Waste disposal surcharge (in $)

C = Cost per lb of treating wastes

F = Conversion factor to transform mg/l to lb/million cu ft

V = Wastewater volume in cu ft

SS = Suspended solids (in mg/l)

BOD = Biochemical oxygen demand (in mg/l).

The cost per lb, C, recalculated every year, was currently $0.025/lb. The volume, V, is determined by the water meter minus a retention factor for water consumption. SS and BOD are borrowed from SIC averages.

-- Thirty-five other cities and towns have such charges for industrial customers using the city sewer system. It is believed that increasing numbers of industries will seek to use public services for treating their wastes.

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CHAPTER VI. BENEFITS DERIVED FROM ENHANCED WATER QUALITY

The measurement of water quality benefits involves consideration of goals and criteria, direct and indirect benefit measurements, special measurement problems, and benefits accruing to individual water user groups. These topics are discussed below under four sections.

A. Objectives and Criteria

Much has been written concerning the philosophy behind any undertaking of public expenditure. Among recent writers are Baumol (1) and Eckstein (2). Perhaps the most concise statement is by Abraham Lincoln, as quoted by Samuelson (3): "The legitimate object of government is to do for the people what needs to be done but which they cannot, by individual effort, do at all, or do so well for themselves."

Senate Document 97 (4) states the objective of water projects to be "to provide the best use, or combination of uses, of water and related land resources to meet all foreseeable short and long-term needs." The U. S. Water Resources Council's more recent Procedures for the Evaluation of Water and Related Land Resource Projects (5) enumerates national income, regional development, environmental, and well-being objectives. The national income objective requires that the effect of externalities, wherever they occur, be included in

benefit calculations. Externalities arise whenever the actions of one person or group affect another and no market exists for economically adjusting the effects of such actions. Water pollution is an example of an externality. Most measures to improve water quality produce externalities. There is practically no market in water quality. Everyone affected by a change in water quality suffers or enjoys an externality, and the sum of all such externalities is important in determining the benefits of water quality enhancement.

A basic principle for evaluating the benefits of any public project is the "with/without" criterion. Senate Document 97 requires its use. "The objective of analyzing a prospective project," wrote Howe (6), "should be to assess just what the state of the nation will be with the project (i.e., if the project is built and operated) as contrasted with what the state of the nation will be without the project.... One must realize that this guideline is not the same as looking at the state of the nation before and after the project. Before the project, certain trends will exist, say a growth in agricultural yields. An irrigation project may permit yields to jump even more, but attributing to the project all the change in yield from before the project to what is observed after the project would clearly be erroneous since part of that change would have occurred without the project."

B. Benefit Measurement

Benefits arising from improvements in water quality are generally difficult to measure because there scarcely exists a private market for such quality. For some parameters considered to produce benefits, it is difficult even to imagine a market price being generated. Water quality is, in fact, a classic example of a public good, in that no riparian owner or water user can be denied the benefits of improved water quality regardless of his investment in water treatment. Nonetheless, two major methods exist for assigning dollar values to increased water quality: (1) measurement of willingness to pay, and (2) substitution of alternative cost.

1. Willingness to Pay

It seems reasonable, in the absence of information concerning the value of an item, to ask how much someone might be willing to pay for that item. If someone knew how much he would be willing to pay for an item, and that item were given to him free of charge, one might argue that he was better off by the amount he was willing to pay. This is the basis of the measurement of benefits by willingness to pay. In order to measure benefits due to increased water quality, one should first determine who would make use of the higher quality water, for whatever purpose, and then interview a representative sample to determine the aggregate willingness

to pay. The sum of all hypothetical payments would be the gross benefit of the higher quality water. The net benefit is obtained by deducting the cost of the project.

If willingness to pay is determined for a number of different water qualities, then a curve relating quality to willingness to pay can be drawn. The marginal benefit of enhancing water quality is the slope of that curve, i.e., the amount of benefit generated by a unit increase in quality from a particular quality. This marginal benefit is sometimes called the "shadow price" of that quality. Generally, the marginal benefit (shadow price) is assumed to decrease with increasing water quality. Therefore, if the shadow price is multiplied by the total increase in water quality, then, for the higher quality levels, the result would be less than the total willingness to pay for the increase in water quality. The difference between willingness to pay and the product of the shadow price and the amount of quality provided is called "consumer surplus." -- When figuring benefits by the method of willingness to pay rather than by the shadow price and quality provided, consumer surplus is automatically included in the measurement.

Willingness to pay is the appropriate measure of benefits when the water quality would not have been upgraded without the project for which the benefit measurement is done. This is an important point. Consider the case in which a private firm might upgrade water quality

at a lower cost than that of a proposed project. Using willingness to pay as a measure of benefits, a favorable benefit-cost ratio might be found for the government project. Yet the project is clearly economically inefficient. Margolis (7) presents an excellent theoretical discussion of willingness to pay and shadow prices.

Many difficulties arise in trying to use willingness to pay as a measure of benefits, not the least of which is the water user's lack of information concerning the ramifications of changes in water quality. Also, when users do understand their water quality situation, they will tend to either under- or overstate their preference for high quality water, depending on whether or not they perceive that a payment will be required for an increase in quality. Kneese and Bower (8) treat these problems in some detail.

To overcome these difficulties, many authors have attempted to establish potential users' willingness to pay by inference, from their behavior patterns. Many of these studies concern recreational demand. Clawson and Knetch (9) related travel costs and time of travel to willingness to pay for recreation. Unfortunately, this expedient is applicable only to relatively remote recreation facilities. Also, according to Cicchetti _et al_. (10), many studies of willingness to pay for recreation have confused the demand for recreation (which is derived from willingness to pay) with projected use of public parks. Use projections

take into account not only demand but also supply, and so represent but a single point on a curve of willingness to pay. Additional data are necessary if economic benefits are to be estimated.

A more dependable solution to the problem of determining willingness to pay, when the opportunity arises, might consist of establishing the willingness of the population to accept a bid or firm offer for the construction of an unauthorized alternative water quality improvement project. The bid might even consist of several cost estimates corresponding to various degrees of water purification. If a majority of respondents are willing to accept one or the other of the cost estimates contained in the offer, the cost of the alternative project is a legitimate measure of the gross benefit attached to the government project.

Another means of determining willingness to pay might be the development of a demand schedule or function. While the implementation of the method may present great difficulties, the theoretical approach for establishing a demand function for water of varying quality has been designed by Ernst & Ernst (25) in a report sponsored by the Corps of Engineers. The demand function indicates the quantity of a given good the consumer desires, at any price and income level, on the assumption that utility (satisfaction) is maximized.

Required model inputs include:

C	= Quantity of an all-purpose good (exclusive of water) consumed by Mr. i per time period.
q, T	= Quantities of water (q) and contaminant (T) used by Mr. i per time period.
p_g, p_w	= Unit prices of good and water, respectively
M	= Mr. i's spendable income
U (G, q, T)	= Mr. i's utility function
f(q, T)	= Water quality indicator function (T/q would be a contaminant concentration ratio)

Mr. i. wants to consume quantities G, q, and T so as to maximize U (G, q, T), subject to: $M = p_g G + p_w q$, and to: f (q, T) = s, where s = a specified water quality standard.

The problem may be solved through the optimization method of Lagrange multipliers. In the following Lagrangian function, A and B are the to-be-determined multipliers:

$$L = U(G, q, T) + A(M - p_g G - p_w q) + B(f(q, T) - s)$$

The function L is maximized with respect to the three decision variables (G, q, T) and the two multipliers (A and B) by finding what values will cause their five respective derivatives to equal zero simultaneously. The optimal desired quantity of water is written as:

$$q = E\ (p_w, p_g, M, s)$$

This is Mr. i's demand function for water of quality s. The effect on q due to a change in quality can be ascertained by evaluating the partial derivative of E with respect to s, namely delta E/delta s. This measures how Mr. i's demand curve for water shifts in response to a specified change in quality, when price and all other factors are held fixed.

For the purposes of this report, which is concerned with assessing the changing value of a water supply of varying quality, the above water quality demand model, as developed and formulated by Ernst and Ernst appears to have limited applicability. The classical economic demand model does not apply well to water quality. Residential water customers do not greatly vary their quantitative water intake with quality changes. They might buy bottled drinking water; but while this would substantially increase their water bills, it would not reduce their demand for tap water by more than an order of magnitude of 1%.

True, there can be trade-offs between quantitative and qualitative water increments. But water customers are not usually denied additional amounts of water they wish to use. Such choices are left to their discretion, and remain fairly independent of water quality.

For the purposes of the present chapter, which deals with the evaluation of benefits derived from enhanced water quality, the Ernst and Ernst water quality demand functions cannot, in their present form, be used to determine the water customer's willingness to pay for enhanced quality. Perhaps the model might be modified to accommodate that requirement. Quality would have to be substituted for quantity, in order that the following questions be answerable: What degrees of water quality enhancement would customers require before agreeing to given increments in their water bills? Or: What increments in water costs would customers consent to pay for given degrees of water purification? An answer to the latter question would express the willingness to pay with which we are concerned.

Willingness to pay for incremental water quality, if it can be evaluated, is a measure of benefits derived from the use of better quality water.

2. Alternative Costs

Alternative cost techniques may be the most useful in determining the benefits associated with increased water quality. Assuming that a given level of water quality will be supplied, one way or another, the gross benefits associated with a project which achieves that quality can be measured by the minimum cost of all other means of providing that quality.

Alternative cost, as a measure of benefits, supersedes willingness to pay as soon as an alternative project is authorized which will be constructed if the public project is not implemented. Should the alternative project cost less than the willingness to pay, the benefit associated with the public project should be computed at the lower of the two, namely at the level of the alternative cost. But should the alternative project cost more than willingness to pay, it should be concluded that since the population is willing to pay for the alternative project, the amount attributed to willingness to pay was actually an understatement of real willingness; again, alternative cost supersedes willingness to pay as a method for evaluating benefits. Thus, applicability of the two methods may be circumscribed by saying: So long as the cost of an authorized alternative project is available for determining benefits, alternative cost is used; if unavailable, the less dependable method of willingness to pay is resorted to as a substitute. However, willingness to pay may include willingness to accept a firm offer for the construction of an unauthorized alternative project.

Consider the following example: A city is contemplating the construction of an upstream reservoir for water supply. The city will also have to build a waste treatment plant so as to maintain a given water quality downstream. The cost of both reservoir and treatment plant is 20 million dollars. A different plan is proposed, say by the Corps of Engineers, for including flow augmentation storage in the reservoir. This will allow a reduction in the efficiency of the treatment plant, while maintaining the same minimum stream quality. The cost of the government project is $18 million. Figuring the benefits accruing to this expansion of the reservoir by alternative cost techniques is appropriate, since the end result, water supply and water quality, is the same in both cases. The gross benefits for the larger dam and reservoir and less efficient treatment plant are $20 million.

Kneese and Bower (8) stated that "water quality is primarily a matter of avoiding costs," and then proceeded to distinguish between damage costs (incurred when water of inferior quality damages clothing, plumbing, or even health) and treatment costs (incurred to improve water quality).

One of the first comprehensive attempts at providing means of evaluating benefits was made by Krutilla and Eckstein (11) when they wrote: "Evaluation of benefits provided by a project involving direct interdependence with other fiscally independent production units requires

crediting the value of external economies and debiting the cost of external diseconomies from the estimate of project benefits taken into account." To the extent that such economies and diseconomies represent, respectively, the cost of private actions which would have been taken in the absence of the proposed project and the private profits or benefits foregone, alternative cost is an appropriate measure of benefit.

Steiner (12) explained the appropriate use of alternative cost. When a government project provides goods or services that would have been provided by private enterprise, the [illegible] reduction in private cost due to non-provision of the same goods or services is attributable to the government project as gross benefits. If there is a difference in the amount of goods or services provided with and without the project, then the gross benefits arising from the difference in amount of goods and services (evaluated by willingness to pay) is either added to or subtracted from the private cost, depending on whether the government project provides a greater or lesser amount of goods or services, respectively. Net benefits may then be obtained by subtracting gross government costs.

It cannot be overstated that the private alternative must be viable, that is, that it would be built in the absence of the government project. Neglect of this condition on the use of alternative

cost can lead to ridiculous results. Consider the construction of a bridge from New York to London, cost $600 billion, and the next best alternative, a tunnel, cost $1 trillion. Obviously there is something wrong with the conclusion that the United States should build the bridge and pay off its national debt with the savings. -- If there is no viable private alternative, then willingness to pay becomes the appropriate measure of benefits.

3. Equivalence of Damages Avoided and Alternative Costs

When improvements in water quality lead to reductions in damages caused by the use of water of inferior quality, the reduction in damages can be counted as a benefit in exactly the same manner as an alternative cost. The two concepts are in fact identical. The damages avoided are measured in terms of the costs incurred. These costs would, in fact, have occurred if no water quality improvement had taken place. Consequently, the with/without criterion is met, and the damages avoided are alternative costs.

4. Land Values

Increases in land values have been used as partial measures of benefits associated with increases in water quality. In general it is difficult to separate the portion of the land value attributable to water quality. If such a value can be determined, then it represents a minimal estimate of the value of clean water, since consumer surplus

is not included in the selling price of land but is properly included as a benefit.

C. Special Problems in Benefit Evaluation

1. Stochastic Nature of Water Quality

At any point in a lake or stream, water quality varies constantly. This makes it quite impossible to derive an exact appraisal of value from a static set of conditions. In determining benefits associated with various levels of quality, this limitation has so far been ignored. In general, with the present lack of sophistication in techniques for measuring benefit, this qualitative variability cannot be taken into account, and its real effect on benefits is unknown. Pollution control systems are therefore designed to accommodate some worst case, often the ten-year seven-day low flow. The costs and benefits of various other means of dealing with natural variation in water flow and quality have not been adequately explored.

When benefits are used in calculations, expected values are appropriate. The expected value of such benefits may be calculated if the probability distribution of water quality parameters is known for those (hopefully few) parameters which may be critical. If but one parameter affects benefits at the general water quality levels expected, then the sum of the products of the probability of occurrence of successive

brackets of water quality and the benefits expected within each respective bracket is the expected value of benefits.

Water quality benefits are also subject to other time variations. Technological change and economic uncertainty provide additional cause for stochastic benefit behavior. When water quality variations have been routinely incorporated into benefit equations, it will be well to make allowances also for probable technological and economic fluctuations.

Upton (13) showed that certain problems of uncertainty can be dealt with explicitly; in particular, effects caused by variance in streamflow. A normal distribution of the variance is assumed. If standards are to be met a large fraction of the time, the size of that fraction and the streamflow variance will determine a critical value, f_o, for flow. If treatment is designed so that standards are satisfied at this critical flow, then they will be met the required fraction of the time. The larger the variance of flow, the lower will be the critical flow. Variance in streamflow increases the required treatment of wastes.

The standard deviation of streamflow in the U.S. has been estimated by Fiering (14) at 25% of the mean. This, however, is an average, and not necessarily representative of a particular stream.

2. Time Discounting of Benefits

Water quality benefits need not be discounted any differently from benefits accruing to any other function of a project. However,

some authors have held that there are long-term opportunity costs associated with polluted water. Parker and Crutchfield (15) stated their case as follows:

> Pollution of water by one user often precludes benefits from some alternative use which would have shown a significantly higher growth rate over time. This results in a systematic and disturbingly large understatement of the real cost of water pollution.
>
> The term "overall cost" as related to water pollution refers to the net loss of benefits that would have accrued if the water resource in question had not been used for the disposal of wastes.
>
> The essential object of public policy must be to minimize the aggregate costs involved, including the costs of prevention and/or abatement, and the opportunity costs of benefits foregone or reduced by lower water quality.
>
> Some of the major social costs of pollution involve the curtailment or loss of amenity water uses, the demand for which is highly elastic to income, whereas supply functions are typically inelastic.

Time differentials may complicate the use of alternative cost to determine benefits. Consider the case in which a Corps proposal is to construct a reservoir some 10 years prior to the time the identical reservoir will otherwise be constructed by another agency, public or private. Certainly the results of the two alternatives are the same, but only after a ten-year period. This problem is accounted for as follows: If the Corps builds now, the alternative cost is the cost of the same project at the time it would have been built, discounted to present value. Because the projects in this case are identical, if

C is the cost of the Corps project, then $(\frac{1}{1+i})^{10} \cdot C$ = the alternative cost, where i is the appropriate discount rate.

However, the benefit streams accruing to the alternatives are also different. After 10 years, the benefits will be assumed identical, but during the first 10 years benefits will accrue to the Corps project and not the private project. The willingness to pay for these additional benefits must be added in the gross benefits of the Corps project. If B is the present value of the first 10 years' benefits, then $\left[(\frac{1}{1+i})^{10} \cdot C\right] + B$ = the gross benefit of the Corps project.

3. Benefits from Preserving Irreplaceable Resources

Problems of irreversible commitments of natural resources can complicate the figuring of costs and benefits. Krutilla and Cicchetti (23) developed an excellent method for comparing the use of unique resources. Benefits for preserving unique resources should be compared not with the traditional concept of the value of the proposed project which destroys them, but with the cost penalty incurred for placing the project elsewhere or accomplishing its results in some other way. In developing a case for the preservation of Hell's Canyon, they pointed out that while the Canyon provides some $900,000 of recreational benefits per year, benefits which would be lost if the Canyon were to be dammed, the additional cost of generating the electricity not provided by the dam, using a steam-electric plant, would be only $80,000 per year.

4. Non-Market Benefits

For many important benefits of clean water, it is impossible to find monetary or even quantifiable equivalents. These benefits should not be included in the economic evaluation of water quality except in presentation. When the evaluation is presented, these non-monetary considerations should be tabulated in a manner which facilitates comparison of their non-monetary values at a glance. Luna Leopold (24) has devised a method for such displays by describing an area in terms of the uniqueness of its particular characteristics or combinations of characteristics.

D. Benefits Accruing to Various Categories of Users

Certain benefits from instream or lake water quality improvement are likely to accrue to particular categories of users. Nemerow and Faro (16) set down guidelines for determining total benefits of a given increase in water quality. Listing all uses which either affect, or are affected by, stream water quality, they computed the sums of values or costs accruing to each use. Categories considered as uses included recreation (benefits measured by willingness to pay or actual expenditures); withdrawal for municipal, industrial, agricultural and rural use (benefits measured by treatment costs avoided in lieu of alternative costs); waste disposal (same method); land aesthetics (benefits estimated from land values on physically comparable clean

and polluted shores); and instream habitat for fish and other biota (benefits measured by willingness to pay for commercial fishery, etc.). Results of applying such evaluations to Lake Onondaga indicated that recreation accounted there for over half of the benefits attributable to increased water quality.

Stone *et al*. (17) attempted to attach to different water uses a priority rank based on a consensus from a large sampling of expert opinion. Such approaches, while providing no absolute scale of values for the measure of benefits, may furnish to planners data helpful in designing projects which will promote local and national support.

1. Public and Industrial Water Supply Customers

The health hazard incident to unsanitary drinking water has been greatly reduced by technological advances. As a result, concluded Gutmanis (18), the effects of water quality in promoting human health in the U. S. may play but a small role in determining benefits of water quality projects.

Other benefits may be more substantial. One benefit likely to accrue to water supply users stems from a reduction in the cost of repair and replacement of water appliances and facilities when total dissolved solids or hardness are reduced. The U.S. Office of Saline Water published three studies of damages associated with municipal

and industrial use of water containing high salinity or hardness (19, reviewed in Chapter II, B, 2), (20), (21). Chapter VII presents an example of benefits derived from avoiding such damages.

Costs for raw water treatment by municipalities and industries may also be reduced by water quality enhancement, thereby providing some additional benefits.

2. Patrons of Water-Based Recreation

Users of water-based recreation facilities probably benefit most from improvements in water quality. The highest damages to recreation are wrought by pollution resulting in prohibited use of existing facilities.

The usual measure of benefits derived from water quality improvement is willingness to pay, or actual expenditures by the public for utilizing recreational opportunities. As indicated in Section B, 1, a number of substitutes for these have also been proposed.

Supplement No. 1 to Senate Document 97 (22) provides a schedule of benefits for various recreational activities on a user-day basis. No support for the figures appearing in that document has ever been presented.

3. Users of Waste-Assimilative Capacity

Users of the waste assimilative capacity of streams and rivers will benefit little if at all from in-stream water quality improvements unless present laws are changed. In particular, section 301 of title III of the Federal Water Pollution Control Act Amendments of 1972 imposes strict effluent limitations on waste dischargers, with the goal of eliminating all discharges by 1985.

Whether or not the Amendments induce 100% compliance, it is perhaps of theoretical interest to state what the benefits of a river's water quality improvements might be for those using the river as a waste conveyor. Where water quality standards have been established, any water quality improvement to a level above the standard permits limited use of the river for the disposal of waste. In that case, the benefits of water quality improvement can be measured by the avoided cost of having to treat effluents. Users would certainly be willing to pay any amount below that cost for the advantage of not having to treat their wastes.

4. Recipients of Well-Being and Aesthetic Enjoyment

Benefits related to well-being and aesthetic pleasure due to improved water quality accrue not only to users of water-based recreational facilities, but to all who live, work, or travel near the water. These benefits can take the form of increased safety while swimming or scuba-diving, of increased well-being in the solitude of wild, unspoiled rivers and mountain lakes, or of increased enjoyment when contemplating

pure water resources. There is also a relaxing peace of mind in the knowledge that a river conveys clean water. This last benefit requires only that the clean stream exist, not that it be used. -- Well-being and aesthetic benefits are generally very difficult to quantify, quasi-impossible to translate into dollar values.

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CHAPTER VII. ECONOMIC TECHNIQUES FOR OPTIMAL WATER SUPPLY PURIFICATION AND ALLOCATION

Reviewed in this chapter are economic techniques applicable to efficient water supply quality enhancement, optimal quality storage reservoir releases, and optimal water supply allocation from among multiple sources of diverse quality.

A. Optimal Raw Water Supply Purification

1. Marginal Costs and Marginal Benefits

In order to determine, in any particular situation, by how much water quality should be increased so as to maximize net benefits, economic theory tells us that marginal benefits should equal marginal costs. Net benefits (N) are equal to the difference between gross benefits (B) and costs (C):

$$N = B - C$$

From elementary calculus, we know that at the maximum, the derivative of N with respect to increasing water quality Q must equal zero.

Or,

$$\frac{dB}{dQ} - \frac{dC}{dQ} = \frac{dN}{dQ} = 0$$

From this equality can be inferred

$$\frac{dB}{dQ} = \frac{dC}{dQ}$$

Simply stated, the rate of change in benefits with a unit change in quality equals the rate of change in costs with a unit change in quality. This can be verified by noting that when the rate of change in benefits is greater than the rate of change in costs, additional units of net benefits could be obtained by additional units of quality. Conversely, if the rate of change in costs is greater than the rate of change in gross benefits, the net benefit is reduced by increasing water quality. Thus, the maximum net benefit lies where rates of change are just equal.

Costs of enhancing water supply quality have been discussed in Chapter IV. Cost data presented there must now be converted into marginal cost data. Where cost schedules expressed in terms of water quality are available, this is not difficult. Consider the following cost schedule for low flow augmentation by means of a water quality storage reservoir:

Reservoir Flow Rate (cfs)	Construction Cost ($ million)
10	1.5
20	1.8
30	2.0
40	4.0

The marginal cost of increasing flow between 0 and 10 cfs is \$1,500,000 : 10 = \$150,000/cfs; between 10 and 20 cfs, the marginal cost is (\$1,800,000 - \$1,500,000) : 10 = \$30,000/cfs; between 20 and 30 cfs, it is \$20,000 cfs; and between 30 and 40 cfs, \$200,000/cfs. The marginal cost is simply taken to be the slope of the line joining the cost points on a graph.

Where cost schedules are not available, but one cost for a specified size is given, a rule-of-thumb can be used to represent the economies of scale in construction costs. The rule-of-thumb, called the 0.6 power rule, as reviewed by Chilton (1), states that the ratio of the costs of two facilities is equal to the ratio of their sizes raised to the 0.6 power. Where X_1 is the size of facility 1, and X_2 the size of facility 2, C_1 is the cost of facility 1, and C_2 the cost of facility 2,

$$\frac{C_1}{C_2} = \frac{X_1^{0.6}}{X_2^{0.6}}$$

This equation can be solved for C_2:

$$C_2 = \frac{C_1 X_2^{0.6}}{X_1^{0.6}}$$

This equation can be used to generate a schedule of costs whereby a cost curve can be drawn and marginal costs can be obtained. However, marginal costs can be obtained directly for a facility of any size X_2,

given the cost of a particular facility C_1 and its size X_1. This is done by taking the derivative of the previous equation with respect to X_2:

$$\frac{dC_2}{dX_2} = \frac{0.6C_1X_2^{-0.4}}{X_1^{0.6}}$$

This is the marginal cost.

Benefits of enhancing water quality have been discussed in Chapter VI. When benefits can be computed from alternative costs or damages avoided, marginal benefits can be determined in the same manner as marginal costs. When this is not possible, benefit schedules can sometimes be derived from water users' willingness to pay. Intangible benefits, which cannot be measured in economic terms, are not considered here.

Referring to the above example of the construction of a water quality reservoir, assume a schedule of benefits determined by willingness to pay:

Reservoir Flow Rate (cfs)	Willingness to Pay ($ million)
10	1.6
20	2.0
30	2.15
40	2.2

The marginal benefits accruing between 0 and 10 cfs equal \$160,000/cfs; between 10 and 20 cfs, \$40,000/cfs; between 20 and 30 cfs, \$15,000/cfs; and between 30 and 40 cfs, \$5,000/cfs. If flow is

increased beyond 20 cfs, it becomes apparent when cost and benefit schedules are compared that marginal costs ($20,000/cfs) exceed marginal benefits ($15,000/cfs). Conversely, if the flow is less than 20 cfs, marginal benefits ($40,000/cfs) exceed marginal costs ($30,000/cfs), and it pays to provide the additional capacity. Therefore, 20 cfs is the flow which should be provided.

Note that marginal costs may be equal to marginal benefits and yet net benefits may still be negative, the benefit-cost ratio being less than one. If so, the project should not be built. Marginal costs may equal marginal benefits at more than one point. In that case, the size provided should be that at which: (1) marginal costs equal marginal benefits, and (2) net benefits are greatest, or costs plus damages are least.

2. Water Supply Purification

An example will show how an economically efficient improvement in public water supply quality may be computed. A community has a water supply of 10 mgd with 500 ppm of TDS. An incremental 5 mgd is needed. The only available water source has 3000 ppm of TDS. The community plans to build a distillation plant to demineralize a portion of the additional 5 mgd, and blend the product with more brackish water and the existing water supply. The resulting water supply should be of a quality that will minimize costs plus damages.

Computation of Salinity

Quantity Desalted	Existing Supply (mgd)(ppm)(gd of TDS)	Brackish Source (mgd)(ppm) (gd of TDS)	Blended Supply (gd of TDS) (mgd)(ppm)
0	10 x 500 = 5,000	5 x 3,000 = 15,000	20,000 : 15 = 1333
1	10 x 500 = 5,000	4 x 3,000 = 12,000	17,000 . 15 = 1133
2	10 x 500 = 5,000	3 x 3,000 = 9,000	14,000 : 15 = 933
3	10 x 500 = 5,000	2 x 3,000 = 6,000	11,000 : 15 = 733
4	10 x 500 = 5,000	1 x 3,000 = 3,000	8,000 : 15 = 533
5	10 x 500 = 5,000	0 x 3,000 = 0	5,000 : 15 = 333
6	9 x 500 = 4,500		4,500 : 15 = 300
7	8 x 500 = 4,000		4,000 : 15 = 267
8	7 x 500 = 3,500		3,500 : 15 = 233
9	6 x 500 = 3,000		3,000 : 15 = 200
10	5 x 500 = 2,500		2,500 : 15 = 167
11	4 x 500 = 2,000		2,000 : 15 = 133
12	3 x 500 = 1,500		1,500 : 15 = 100
13	2 x 500 = 1,000		1,000 : 15 = 67
14	1 x 500 = 500		500 : 15 = 33
15	0 x 500 = 0		0 : 15 = 0

Desalting costs are derived from Koelzer (2). A three-point cost curve provides a cost schedule:

Plant Capacity (mgd)	Distillation Cost (¢/Kgal)
1	80
10	50
100	40

Cost Schedule and Marginal Cost

Quantity Desalted (mgd)	Salinity (ppm)	Desalting Cost ($/day)	Increment ($/day)	Marginal Cost ($/ppm/day)
0	1,333	0		
			800	4.00
1	1,133	800		
			467	2.33
2	933	1,267		
			466	2.33
3	733	1,733		
			467	2.33
4	533	2,200		
			467	2.33
5	333	2,667		
			466	14.00
6	300	3,133		
			467	14.00
7	267	3,600		
			467	14.00
8	233	4,067		
			466	14.00
9	200	4,533		
			467	14.00
10	167	5,000		
			389	11.67
11	133	5,389		
			389	11.67
12	100	5,778		
			389	11.67
13	67	6,167		
			389	11.67
14	33	6,556		
			388	11.67
15	0	6,944		

A benefit schedule was adapted from data provided by the Black & Veatch study (3) discussed in Chapter II, B, 2. The damage figure of $72/100,000 gallons corresponding to an increase in salinity from 250 ppm to 1750 ppm of TDS, was converted to $720/mgd. The study also

supplied, in support of that damage figure, a series of curves representing partial costs over the entire range of water quality. From these, an aggregate curve could be derived. Damage values were read for 1500, 1250, 1000, 750, and 500 ppm.

Benefit Schedule and Marginal Benefit

Salinity (ppm)	Damage Avoided ($/mg)	Damage Avoided ($15mgd)	Benefit ($/day)	Increment ($/day)	Marg. Benefit ($/ppm/day)
1,750	720	10,800	0		
				900	3.60
1,500	660	9,900	900		
				1,050	4.20
1,250	590	8,850	1,950		
				1,350	5.40
1,000	500	7,500	3,300		
				1,500	6.00
750	400	6,000	4,800		
				2,250	9.00
500	250	3,750	7,050		
				3,750	15.00
250	0	0	10,800		

Benefit Schedule and Marginal Benefit
Converted to Quantity Desalted Basis

Quantity Desalted (mgd)	Salinity (ppm)	Damage Avoided ($/day)	Benefit ($/day)	Increment ($/day)	Marginal Benefit $/ppm/d
0	1,333	9,200	0		
				980	4.90
1	1,133	8,220	980		
				1,120	5.60
2	933	7,100	2,100		
				1,250	6.25
3	733	5,850	3,350		
				1,800	9.00
4	533	4,050	5,150		
				2,800	14.00
5	333	1,250	7,950		
				500	15.00
6	300	750	8,450		
				500	15.00
7	267	250	8,950		
				250	15.00
7.5	250	0	9,200		

Marginal Benefit Vs. Marginal Cost

Salinity Range (ppm of TDS)	Marginal Benefit ($/ppm/day)	Marginal Cost ($/ppm/day)
1,333 - 1,133	4.90	4.00
1,133 - 933	5.60	2.33
933 - 733	6.25	2.33
733 - 533	9.00	2.33
533 - 333	14.00	2.33
333 - 300	15.00	14.00
300 - 267	15.00	14.00
267 - 250	15.00	14.00
250 - 233	0	14.00
233 - 200	0	14.00
200 - 167	0	14.00
167 - 133	0	11.67
133 - 100	0	11.67
100 - 67	0	11.67
67 - 33	0	11.67
33 - 0	0	11.67

Summation of Damage and Cost

Quantity Desalted (mgd)	Salinity (ppm)	Desalting Cost ($/day)	Damage Avoided ($/day)	Damage + Cost ($/day)
0	1,333	0	9,200	9,200
1	1,133	800	8,220	9,020
2	933	1,267	7,100	8,367
3	733	1,733	5,850	7,583
4	533	2,200	4,050	6,250
5	333	2,667	1,250	3,917
6	300	3,133	750	3,883
7	267	3,600	250	3,850
7.5	250	3,833	0	3,833
8	233	4,067	0	4,067
9	200	4,533	0	4,533
10	167	5,000	0	5,000
11	133	5,389	0	5,389
12	100	5,778	0	5,778
13	67	6,167	0	6,167
14	33	6,556	0	6,556
15	0	6,944	0	6,944

In this example, marginal benefits of desalting exceed marginal costs not only for the entire incremental brackish water supply of 5 mgd, but also, provided the brackish supply is desalted first, for one-fourth of the existing freshwater supply, or a total of 7.5 mgd. The mineral content is thereby reduced from 1,333 ppm to 250 ppm of TDS. A 7.5 mgd distillation plant would provide pure water at the cost of $3,833 per day, while the benefit would be $9,200 per day. The benefit-cost ratio would be 2.4; the net benefit would equal $5,367 per day. The minimum total of damage plus cost would also occur at 250 ppm, where it would equal the daily cost of $3,833, damage being reduced to zero.

The marginal-cost and marginal-benefit relationship confirms the optimality of desalting to 250 ppm; at that water quality, the marginal cost would be $14 per ppm per day; while the marginal benefit would be $15. Since, however, the benefit is zero below 250 ppm, further desalting would not pay.

Should the community wish to bring down the salinity to AWWA's goal of 200 ppm, the gross benefit ($9,200/day) would still exceed the cost ($4,533/day) by a good margin, but the net benefit would decrease from $5,367 to $4,667 per day. The benefit-cost ratio would decrease to 2.03. The total of damage and cost would increase from $3,833 to $4,533 per day.

On the basis of the figures used in this example, an economically efficient water quality standard could be established at 250 ppm of TDS. It would apply only to the community described.

For another example of optimal raw water supply purification, consider a group of eight industrial polluters discharging an average of 1.25 mgd, or a total of 10 mgd, into a river. They are being sued for damages by a municipality located downstream which draws its 5-mgd water supply from the river. The municipality has set up a schedule of damages based on its extra treatment costs. All figures used below are taken from tables presented in Chapter IV.

Schedule of Pollution Damages

BOD Removal (percent)	Extra Treatment Costs ($/5 mgd)	Damages Charged ($/day)
0	0	1,313
35	457	856
88	840	473
95	901	412
97	1,313	0

If the polluters can remove the BOD, no charge will be levied, and they will receive a benefit equal to the damages avoided. If they remove a portion of the BOD, the damages levied will be partial. What is the optimum level of BOD removal that will minimize costs plus damages?

The polluters plan to install a certain configuration of artificial aerators into the river for BOD reduction, and want to know how many units to order. The following two tables show costs, marginal costs, benefits, and marginal benefits of removing increments of BOD through the installation of aerating equipment in the river.

Artificial Aeration Cost Schedule and Marginal Costs

Aerators (units)	BOD Removal (percent)	Cost/Year ($)	Cost/Day ($)	Increment ($/day)	Marg. Cost ($/% rem/day)
0	0	0	0		
				114	3.26
3	35	41,500	114		
				86)	
6	--	72,900	200	)	
				80)	4.55
9	--	102,000	280	)	
				75)	
12	88	(129,600)	(355)		
				73)	
15	--	(156,200)	(428)	)	20.71
				72)	
18	95	(182,500)	(500)		
				70)	
21	--	(208,000)	(570)	)	46.50
				23)	
22	97	(216,500)	(593)		

Note: Costs in parentheses are calculated. Those corresponding to aerators above 9 units were extrapolated through the addition of reasonable increments.

Damage Schedule, Marginal Benefits, and Marginal Costs

BOD Removal (percent)	Damages ($/day)	Increment ($/day)	Marg. Benefit ($/% rem/day)	Marg. Cost ($/% rem/day)
0	1,313			
		457	13.06	3.26
35	856			
		383	7.23	4.55
88	473			
		61	8.71	20.71
95	412			
		412	206.00	46.50
97	0			

From the above tables, it can be concluded that total daily benefits of avoiding all damage charges ($1,313) exceed total daily costs of instream aeration ($593) for 97% BOD removal. The benefit-cost ratio is 2.21. The net benefit is $720 per day.

Accordingly, it would seem that the use of 22 aerators to accomplish 97% removal is warranted. Is this confirmed by marginal benefits and marginal costs? These are equated at two levels of BOD removal: First, at the 88% level, after which incremental costs exceed incremental benefits; and second, at the 97% level, after which there are no more benefits. As a result, two solutions appear sound: 88% and 97% BOD removal. What will help the polluters decide between ordering 12 aerator units for 88% BOD removal and 22 units for 97% removal? Here, benefits are not similar to those in the previous example, in which they accrued to different segments of the population, over a long period of time, in an inconspicuous manner. Benefits would accrue as a daily differential cost between the maximum charge for damages and the actual charge. To it is added the cost of aeration. The problem is to minimize the total of these two values. That the total is minimized at 97% BOD removal is shown by the following table:

Minimal Sum of Damages and Cost

BOD Removal (percent)	Damages ($/day)	Costs ($/day)	Damages + Costs ($/day)
0	1,313	0	1,313
35	856	114	970
88	473	355	828
95	412	500	912
97	0	593	593

3. Design of a Water Production Function

Another possible technique for determining economically efficient water supplies is suggested by the Ernst & Ernst report (11) already referred to in Chapter VI, B, 1. They are taking the point of view of a water utility which is in business for profit. Model inputs for the cost schedule are:

x_1	= gallons of raw water per day
x_2	= amount of aggregate treatment used per day
w_1	= unit raw water cost
w_2	= unit treatment cost
F	= investment cost of treatment plant
r	= annual capital charge rate on plant
q	= gallons of treated water output per day
$g(x_1, x_2, F)$	= production function characterizing the treatment plant, as x_1, x_2, and F are transformed into q
I	= impairment in water quality, also represented by h(q); quality being a function explicitly of q, and implicitly of x_1, x_2, and F.

It is desired to minimize, with respect to x_1, x_2, and F, total daily costs of producing a specified amount of treated water (q^*) of a specified quality (I^*):

$$\text{Min } C = w_1x_1 + w_2x_2 + rF$$

subject to:

$$q^* = g(x_1, x_2, F), \text{ and}$$

$$I^* = h(q) = h(g(x_1, x_2, f))$$

This problem is amenable to solution by the standard Lagrange-multiplier constrained-optimization method. With A and H as the to-be-determined multipliers, the relevant Lagrangian function reads:

$$L = w_1x_1 + w_2x_2 + rF + A(q^* - g(x_1, x_2, F)) + H(I^* - h(g(x_1,x_2,F)))$$

Let the partial derivatives of g with respect to x_1 x_2, anf F be represented by g_1, g_2, and g_F; and the derivative of h with respect to q by h'; then, the first-order optimization equations resulting from setting first partials of L (with respect to x_1, x_2, F, A and H) equal to zero can be written as:

(1) $w_1 - Ag_1 - Hh'g_1 = 0$

(2) $w_2 - Ag_2 - Hh'g_2 = 0$

(3) $r - Ag_F - Hh'g_F = 0$

(4) $q^* = g(x_1, x_2, F)$

(5) $I^* = h(q) = h(g(x_1, x_2, F))$.

These five equations are conceptually solvable for the five unknowns x_1, x_2, F, A and H, as functions of the known parameters in the model: w_1, w_2, r q* and I*. The standard long-run cost function C_{LR}, equals Y (prices, q, I*). The marginal cost function which, together with the marginal revenue function, governs a privately owned utility's supply function, is derived by simply differentiating C_{LR} partially with respect to q, as follows:

MC = Yq(prices, q, I*).

The above development of cost functions is presented in Volume I of the Ernst & Ernst report (11); a numerical example (with turbidity as the contaminant) is worked out in Volume II. What has been accomplished here? A technique has been presented for minimizing the sum of various items or cost incurred in providing various quantities of water of a specified quality.

Not achieved by the technique is the determination of the optimal quantity and quality of water which it is economically efficient to produce, given alternative raw water sources, their quality, water and treatment cost, and water quality benefits. This is the problem encountered every day in real life by water resource planners.

B. Optimal Quality Storage Reservoir Releases

Reservoirs both enhance and degrade water quality. Evidence which suggests that water quality is degraded as a result of reservoir operation is provided by Mueller (4) who graphically illustrates the degradation of the bed of the Rio Grande due to pronounced decreases in sediment load caused by the operation of dams. Salt concentrations in water can be noticeably increased by reservoir evaporation. And stagnant water invites stratification, with upper layers rising in temperature and lower layers becoming anaerobic. Nevertheless, reservoirs can be used to increase downstream water quality in terms of dissolved oxygen during periods of low flow. Optimization techniques have been applied to this practice.

The possibilities of increasing water quality in the Potomac River Basin through low flow augmentation have been studied by Jaworski, Weber, and Deininger (5). The water quality parameter of interest was dissolved oxygen. The effects of temperature, stream depth and velocity, biological activity and reaeration rates were explicitly considered. Dynamic programming techniques were used to determine: (a) what water quality could be maintained given a flow requirement, and (b) what releases would be necessary to maintain a given water quality level. The release schedule necessary to achieve these objectives was specified, and least cost construction programs for achieving given levels of DO concentrations in the river were determined.

The study did not, however, take into account the multiple-purpose nature of the reservoirs proposed for the Potomac Basin. Solving the same problem considering these constraints is likely to prove considerably more difficult.

Davis (6) performed an extensive study of the relative cost of low flow augmentation for meeting dissolved oxygen requirements in the Potomac Estuary. He concluded that artificial aeration would be a much more efficient and advantageous means of meeting water quality standards.

ReVelle, Joeres and Kirby (7), ReVelle and Kirby (8), and Eastman and ReVelle (9) have developed a linear programming method for determining the minimum size reservoir which will simultaneously meet requirements for water supply, flood control, and recreation. This method represents one of the many reasonable and useful tools for reservoir design and management. The constraints that require water supply, flood control and other functions to be fulfilled are probabilistic, i.e., the requirements are met a high, or very high, percentage of the time. The model, when solved, specifies an operating policy for the reservoir. It specifies the release of water from the reservoir during a given month as a function of the storage at the beginning of the month such that the requirements are met. It also specifies the optimal reservoir size and cost. Thus, the cost of maintaining a given minimum streamflow can be determined. Further, the marginal cost of maintaining additional flow is given by the value of the appropriate dual variable.

For any given minimum streamflow, a linear program can be solved to determine the cost of necessary wastewater treatment. Thus, the value of any given increment to low flow can be determined, and marginal value (benefit) can be shown graphically. Optimal conditions occur when marginal cost equals marginal benefit.

C. Optimal Water Supply Allocation From Multiple Sources

An abiding problem with water resource planners is the allocation of water supply from among multiple sources of diverse quality. It varies in complexity with the number of sources and, particularly, with the number of water quality parameters included. Problems involving a single quality parameter can be solved and optimized with simple techniques.

1. Water Supply Allocation With a Single Quality Parameter

An example of a multi-source, quantitative and qualitative water supply allocation problem, with opportunities for trade-offs, is presented below. The problem requires a single water quality parameter to be taken into account: TDS. The example illustrates factors and relationships such as:

- Net Benefits
- Benefit-cost ratios
- Marginal benefits and marginal costs
- Summation of damages and costs
- Trade-off opportunities between larger quantities and higher qualities
- Compromise solutions

Reference is made again to the fictitious problem presented in Chapter IV, C, 4. To the earlier assumptions is now added the possibility of reducing the salinity of additional freshwater sources F1 and F2, as well as of renovated wastewater W, to 500 ppm, through application of a membrane desalination process. Desalting the existing supply S, already at the 500-ppm quality level, is not considered. Alternatives are increased from 9 to 35, in a matrix involving 5 quantitative and 7 qualitative requirements.

a. The Problem

Description	Quantity (mgd)	Quality (ppm)
Total Water Requirements	R = 60, 65, 70, 75, 80	r = 800, 700, 600, 500, 400, 300, 200
Existing Water Supply	S = 40	s = 500
Add'l Freshwater Source I	F1 = 24	f1 = 1,200
Add'l Freshwater Source II	F2 = 12	f2 = 1,000
Renovated Wastewater	W = 30	w = 850
Distilled Sea Water	D = infinity	d = 50

The following tables present optimal quantitative and qualitative solutions for all 35 requirements:

Optimal Solutions

Item	Quality (ppm)	Quantity (mgd) 60	65	70	75	80
S		40	40	40	40	40
F1		8	13	18	23	23
F2		12	12	12	12	12
W	800	-	-	-	-	5
D		-	-	-	-	-
R		60	65	70	75	80
S		40	40	40	40	40
F1		8	7	4	2	-
F2		12	12	12	12	12
W	700	-	6	14	21	28
D		-	-	-	-	-
R		60	65	70	75	80
S		40	40	40	40	40
F1		8*	12*	16*	20*	24*
F2		12	12	12	12	12
W	600	-	1	2	3	4
D		-	-	-	-	-
R		60	65	70	75	80
S		40	40	40	40	40
F1		8*	13*	18*	23*	24*
F2		12*	12*	12*	12*	12*
W	500	-	-	-	-	4*
D		-	-	-	-	-
R		60	65	70	75	80
S		40	40	40	40	40
F1		-	-	14*	18*	22*
F2		6*	10*	-	-	-
W	400	-	-	-	-	-
D		14*	15*	16*	17*	18*
R		60	65	70	75	80

Optimal Solutions (Cont'd)

Item	Quality (ppm)	Quantity (mgd) 60	65	70	75	80
S		33	36	38	40	40
F1		-	-	-	-	-
F2		-	-	-	-	2
W	300	-	-	-	-	-
D		27*	29*	32*	35*	38*
R		60	65	70	75	80
S		20	21	23	25	26
F1		-	-	-	-	-
F2		-	-	-	-	-
W	200	-	-	-	-	-
D		40*	44*	47*	50*	54*
R		60	65	70	75	80

* Desalination is needed.

NOTE: The above table was prepared in a manner similar to that used for the three schedules in Chapter IV, C, 4, with the added possibility of applying a membrane desalting process to F1, F2, and W.

Quantities of Water in Need of Desalination (mgd)

Quality (ppm)	60	65	70	75	80
	Membrane Process				
800	-	-	-	-	-
700	-	-	-	-	-
600	8	12	16	20	24
500	20	25	30	35	40
400	6	10	14	18	22
300	-	-	-	-	-
200	-	-	-	-	-
	Distillation Process				
800	-	-	-	-	-
700	-	-	-	-	-
600	-	-	-	-	-
500	-	-	-	-	-
400	14	15	16	17	18
300	27	29	32	35	38
200	40	44	47	50	54

b. Desalination Cost Schedule

Desalting costs are derived, as in Section A, 2, from Koelzer (2):

Capacity (mgd)	Distillation (¢/Kgal)	Membrane (¢/Kgal)
1	80	50
10	50	30
100	40	20

By plotting these costs on graph paper, one obtains cost curves from which a cost schedule can be derived, and marginal costs can be computed:

Desalting Cost Schedule and Marginal Costs

Quantity (mgd)	Distillation Process Cost ($/day)	Distillation Process Marg. Cost ($/mgd)	Membrane Process Cost ($/day)	Membrane Process Marg. Cost ($/mgd)
1	800		500	
		520		350
2	1,320		850	
		510		330
3	1,830		1,180	
		490		310
4	2,320		1,490	
		480		290
5	2,800		1,780	
		470		280
6	3,270		2,060	
		450		260
7	3,720		2,320	
		440		240
8	4,160		2,560	
		430		230
9	4,590		2,790	
		410		210
10	5,000		3,000	
		410		210
20	9,100		5,100	
		410		210
30	13,200		7,200	
		400		200
40	17,200		9,200	
		390		190
50	21,100		11,100	
		390		190
60	25,000		13,000	
		380		180
70	28,800		14,800	
		380		180
80	32,600		16,600	
		370		170
90	36,300		18,300	
		370		170
100	40,000		20,000	

By means of this cost and marginal cost schedule, daily dollar costs can be computed for the 35 alternatives:

Desalination Cost Schedule
($/day)

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
	Membrane Desalting Costs				
800	-	-	-	-	-
700	-	-	-	-	-
600	2,560	3,420	4,260	5,100	5,940
500	5,100	6,150	7,200	8,200	9,200
400	2,060	3,000	3,840	4,680	5,520
300	-	-	-	-	-
200	-	-	-	-	-
	Distillation Costs				
800	-	-	-	-	-
700	-	-	-	-	-
600	-	-	-	-	-
500	-	-	-	-	-
400	6,640	7,050	7,460	7,870	8,280
300	11,970	12,790	14,000	14,800	16,400
200	17,200	18,760	19,930	21,100	22,660
	Total Costs				
800	-	-	-	-	-
700	-	-	-	-	-
600	2,560	3,420	4,260	5,100	5,940
500	5,100	6,150	7,200	8,200	9,200
400	8,700	10,050	11,300	12,550	13,800
300	11,970	12,790	14,000	14,800	16,400
200	17,200	18,760	19,930	21,100	22,660

c. Desalination Benefit Schedule

With desalting costs computed for the 35 alternatives, benefits of providing water in identical quantities and qualities need to be developed. To avoid the complications of potential (uncertain) and future benefits (those accruing only at the time of actual water use),

it is assumed that any excess water not needed at the time the water project is completed can be sold to industry at a uniform rate of 20 ¢/Kgal, or $200 per million gallons.

As in Section A, 2 of the present chapter, the benefit schedule which follows is taken from the Black & Veatch study (3) reviewed in Chapter II, B, 2. A single aggregate damage figure, for an increase in salinity from 250 ppm to 1750 ppm of TDS, was provided by that study. It reads $72/100,000 gallons (per year per customer), which equals $720/million gallons (per day per 365 customers). However, from a number of curves in the study representing partial costs, an aggregate curve was derived. From the aggregate curve, damage values were read for 200, 300, 400, 500, 600, 700, and 800 ppm of TDS:

Schedule of Damages and Benefits

Salinity (ppm of TDS)	Damage ($/mgd)	Benefit ($/mgd)
800	420	0
700	375	45
600	320	100
500	250	170
400	165	255
300	65	355
200	0	420

From the above figures can be developed a benefit schedule for various quantities and qualities:

Gross Benefit Schedule
($/day)

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
800	0	1,000	2,000	3,000	4,000
700	2,700	3,925	5,150	6,375	7,600
600	6,000	7,500	9,000	10,500	12,000
500	10,200	12,050	13,900	15,750	17,600
400	15,300	17,575	19,850	22,125	24,400
300	21,300	24,075	26,850	19,625	32,400
200	25,200	28,300	31,400	34,500	37,600

Note: The above figures include credits for excess water sold at 20 cents per 1000 gallons, as follows:

60 mgd: $ 0/day
65 mgd: 1,000/day
70 mgd: 2,000/day
75 mgd: 3,000/day
80 mgd: 4,000/day

d. Net Benefits

With the help of the above tables, it is possible to analyze various relationships as guides in selecting an advantageous solution. The following table, prepared by deducting costs from gross benefits for the 35 alternatives, shows net benefits:

Net Benefits
($/day)

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
800	0	1,000	2,000	3,000	4,000
700	2,700	3,925	5,150	6,375	7,600
600	3,440	4,080	4,740	5,400	6,060
500	5,100	5,900	6,700	7,550	8,400
400	6,600	7,525	8,550	9,575	10,600
300	9,330	11,285	12,850	14,825	16,000
200	8,000	9,540	11,470	13,400	14,940

This table indicates that net benefits tend to increase with the quantity of water provided and with the purity of the supply. The highest net benefit, $16,000 per day, occurs when an 80-mgd supply is treated to a quality of 300 ppm of TDS. The 300 ppm quality level shows the highest net benefits for all quantities. Thanks to the special credit given for the sale of excess water, net benefits always increase with quantity.

e. Benefit-Cost Ratio

Gross benefits divided by costs for each alternative are shown in the following table of benefit-cost ratios:

Benefit-Cost Ratios

Quality (ppm)	Quantity (mgd)				
	60	65	70	75	80
800	--	inf.	inf.	inf.	inf.
700	inf.	inf.	inf.	inf.	inf.
600	2.34	2.19	2.11	2.06	2.02
500	2.00	1.96	1.93	1.92	1.91
400	1.76	1.75	1.76	1.76	1.77
300	1.78	1.88	1.92	2.00	1.98
200	1.47	1.51	1.58	1.64	1.66

Note: inf. = infinity.

Ratios are favorable throughout the range of quantities and qualities considered. Ruling out infinity (where benefits accrue at no cost), benefit-cost ratios range from 1.47 for 60 mgd with 200 ppm, to 2.34 for the same quantity with 600 ppm. Ratios decrease as quality increases, recovering somewhat at the 300 ppm level.

f. Marginal Benefits Vs. Marginal Costs

The behavior pattern of marginal benefits in relation to that of marginal costs is a powerful clue to economic efficiency. The next two tables, derived from the desalting cost schedule and benefit schedule, show marginal costs and marginal benefits:

Marginal Cost Matrix

Costs opposite each quality level are in \$/day;
Marginal costs are in \$/ppm/day.

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
800	0	0	0	0	0
Marg. Cost	0	0	0	0	0
700	0	0	0	0	0
Marg. Cost	25.60	34.20	42.60	51.00	59.40
600	2,560	3,420	4,260	5,100	5,940
Marg. Cost	25.40	27.30	29.40	31.00	32.60
500	5,100	6,150	7,200	8,200	9,200
Marg. Cost	36.00	39.00	41.00	43.50	46.00
400	8,700	10,050	11,300	12,550	13,800
Marg. Cost	32.70	27.40	27.00	22.50	26.00
300	11,970	12,790	14,000	14,800	16,400
Marg. Cost	52.30	59.70	59.30	63.00	62.60
200	17,200	18,760	19,930	21,100	22,660

Source: Table in Sub-section 1, b, entitled "Desalination Cost Schedule."

Marginal Benefit Matrix

Benefits opposite each quality level are in $/day; Marginal benefits are in $/ppm/day.

Quality (ppm)	60	65	70	75	80
800	0	1,000	2,000	3,000	4,000
Marg. Ben.	27.00	29.25	31.50	33.75	36.00
700	2,700	3,925	5,150	6,375	7,600
Marg. Ben.	33.00	35.75	38.50	41.25	44.00
600	6,000	7,500	9,000	10,500	12,000
Marg. Ben.	42.00	45.50	49.00	52.50	56.00
500	10,200	12,050	13,900	15,750	17,600
Marg. Ben.	51.00	55.25	59.50	63.75	68.00
400	15,300	17,575	19,850	22,125	24,400
Marg. Ben.	60.00	65.00	70.00	75.00	80.00
300	21,300	24,075	26,850	29,625	32,400
Marg. Ben.	39.00	42.25	45.50	48.75	52.00
200	25,200	28,300	31,400	34,500	37,600

Source: Table in Sub-section 1, c, entitled "Gross Benefit Schedule."

As may be noted from comparing the above two tables, marginal benefits generally exceed marginal costs. Exceptions are: Between 700 and 600 ppm, for 70 mgd and more; and between 300 and 200 ppm, for all quantities. Marginal costs and marginal benefits are equated, for 60 and 65 mgd, at 300 ppm only; for 70, 75, and 80 mgd, at 600, 500, and 300 ppm of TDS. For the latter quantities, quality enhancement should not be brought below 600 ppm unless it is intended to proceed further to below 500 ppm. The result generally confirms the signal given by net benefits.

g. Summation of Damages and Costs

Before damages and costs can be summed up, a schedule of damages is first derived from the table in Sub-section 1, c, entitled "Schedule of Damages and Benefits," where damages are shown in dollars per mgd:

Damage Schedule
($/day)

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
800	25,200	27,300	29,400	31,500	33,600
700	22,500	24,375	26,250	28,125	30,000
600	19,200	20,800	22,400	24,000	25,600
500	15,000	16,260	17,500	18,750	20,000
400	9,900	10,725	11,550	12,375	13,200
300	3,900	4,225	4,550	4,875	5,200
200	0	0	0	0	0

To the above damages are now added costs for corresponding alternatives:

Sum of Damages and Costs
($/day)

Quality (ppm)	Quantity (mgd) 60	65	70	75	80
800	25,200	26,300	27,400	28,500	29,600
700	22,500	23,375	24,250	25,125	26,000
600	21,760	23,220	24,660	26,100	27,540
500	20,100	21,400	22,700	23,950	25,200
400	18,600	19,775	20,850	21,925	23,000
300	15,870	16,015	16,550	16,675	17,600
200	17,200	17,760	17,930	18,100	18,660

Note: The credit for selling excess water has been deducted from the sum of damages and costs.

For all quantities, totals are lowest at the 300-ppm quality level. Totals invariably increase with quantity, despite the special credit given for selling excess water.

h. Trade-Off Opportunities Between Quantity and Quality

An examination of several of the tables indicates opportunities for trade-offs between quantity and quality levels. Similar gross costs or similar gross benefits, by themselves, may not be too meaningful. But similar net benefits may present real possibilities for switches:

Trade-Off Opportunities

Quantity (mgd)	Quality (ppm)	Net Benefit ($/day)		Quantity (mgd)	Quality (ppm)	Net Benefit ($/day)
60	500	5,100	Versus	70	700	5,150
60	400	6,600	Versus	70	500	6,700
65	400	7,525	Versus	75	500	7,550
70	400	8,550	Versus	80	500	8,400
65	200	9,540	Versus	75	400	9,575
65	300	11,285	Versus	70	200	11,470
75	300	14,825	Versus	80	200	14,940

Possible trade-offs at the top of the table do not appear attractive. The last two or three are more lucrative. What may help decide between a larger quantity or a higher quality is the cost schedule. Out-of-pocket costs are much lower ($12,550/day) for a 75-mgd water supply with 400 ppm of TDS than for a 65-mgd supply with 200 ppm ($18,760/day). Because of the high cost of desalination, costs are also much lower for 65 mgd with 300 ppm than for 70 mgd with 200 ppm, and for 75 mgd with 300 ppm than for 80 mgd with 200 ppm of TDS.

Trade-offs on the basis of nearly equal benefit-cost ratios are much less meaningful. The sum of damages and costs affords several opportunities, of which the lowest totals are most advantageous: 75 mgd with 300 ppm ($16,675/day) is not far above the lowest sum, that for 60 mgd with the same quality ($15,875/day).

i. Compromise Decisions

In this example, benefits accrue to individual domestic water customers over a period of time in the form of lower repair and replacement costs. They are less conspicuous to political leaders than immediate cash outlays for desalting. The solutions that have the best chances of receiving support in real life are likely to be compromises between those soundest in the long run, according to economic theory, and those found most expedient by city fathers and government officials with an eye on the public purse.

Net benefits, marginal benefits equaling marginal costs, and damages plus costs -- all favor a quality of 300 ppm. But whereas, at that quality level, it would take a large sacrifice in net benefits to meet the minimum sum of damages and costs which occurs at 60 mgd (the net benefit being reduced from $16,000 to $9,330 per day), it would take a small sacrifice in the total of damages and costs to meet the maximum net benefit which occurs at 80 mgd (the sum of damages and costs being increased from $15,870 to $17,600 per day). This militates in favor of an 80 mgd supply with 300 ppm of TDS.

The cost consciousness of the city fathers may make them wish to consider, in addition to the above evidence, some of the compromises and trade-offs shown in the table below. Each pair of alternatives shown below the optimal solution lies on a cost level providing trade-off opportunities. Net outlays may help planners to decide.

Potential Compromises and Trade-Offs

Quantity/Quality (mgd/ppm of TDS)	Desalting Cost ($/day)	Net Outlay* ($/day)	Net Benefit ($/day)	Net Damage + Cost* ($/day)
80/300	16,400	12,400	16,000	17,600
70/300	14,000	12,000	12,850	16,550
80/400	13,800	9,800	10,600	23,000
65/300	12,790	11,790	11,285	16,015
75/400	12,550	9,550	9,575	21,925
60/300	11,970	11,970	9,330	15,870
70/400	11,300	9,300	8,550	20,850
60/400	8,700	8,700	6,600	18,600
75/500	8,200	5,200	7,550	23,950
60/500	5,100	5,100	5,100	20,100
75/600	5,100	2,100	5,400	26,100

*Net after deduction of income from the sale of excess water.

From this table, it may be gathered that the most attractive quantity/quality trade-offs based on desalting costs, if net outlays are to be minimized, are the second in each couple of alternatives. If quality is of paramount interest, the lowest net outlay for 300 ppm water is $11,790 at 65 mgd; for 400 ppm, $8,700 at 60 mgd; for 500 ppm, $5,100 at 60 mgd. If supply quantity is of concern for the future,

then 80 mgd/400 ppm may be obtained at a net outlay of $9,800 per day; 75 mgd/500 ppm, at $5,200; 75 mgd/600 ppm, at $2,100. Which, of quantity, quality, and net outlay will exert the strongest pull? Perhaps 70 mgd/400 ppm at a net outlay of $9,300/day would appear an acceptable compromise.

2. Water Supply Allocation With Multiple Quality Parameters

Where more than one quality parameter is to be taken into account, the above procedure becomes inadequate. More sophisticated techniques are necessary. However, certain sacrifices must be accepted.

In the first technique described below, no provision is made for upgrading the quality of the water sources. Neither is an attempt made to determine net benefits, cost-benefit ratios, marginal costs or marginal benefits, or the summation of damages and costs. Although quantity and quality levels can be relaxed from set constraints after cost minimization has been achieved, it is necessary to decide in advance what the total water quantity and the concentration of each quality parameter in the blended supply shall be. Cost limitations are not taken into account at first. The technique is, thus, round-about, and may require a good deal of iteration of computer runs if all aspects are to be weighed against one another for an acceptable compromise.

The problem is stated as follows: Given N alternative sources of raw water, each with a known maximum supply, each containing a given

concentration of up to M types of impurities, and available at a known cost per gallon -- minimize the cost of providing a given total amount of water with a maximum concentration of each of the M impurities.

Define:

Q_i = the maximum yield of source i (gpd)

c_{ij} = the concentration of impurity j in water from source i

T = total amount of water required (gpd)

K_i = the cost of water from source i (\$/gpd)

C_j = the maximum allowable concentration of impurity j in the final blended water

q_i = the amount of water to be taken from source i (to be determined) (gpd)

The objective is to minimize the cost of providing water. This cost is the sum of all the q_iK_i for $i = 1$ to N, that is the sum of the costs of the water taken from each of the N sources. This objective can be written:

$$\text{Min} \sum_{i=1}^{N} q_iK_i .$$

We are constrained to supply at least T gallons of water. This means that the sum of the q_i ($i = 1$ to N) must be equal to or greater than T, or $\sum_{i=1}^{N} q_i \geq T$. Also, the amount of water supplied from source i can be no greater than Q_i (all i, $i = 1$ to N). The equivalent mathematical statement is $q_i \leq Q_i$ ($i = 1$ to N). All the constraints on the quantity of water have now been specified.

The constraints on the final quality of the water are equally easy to formulate. The total amount of impurity j in the final water which comes from source i is proportional to $c_{ij}q_i$. The total amount of impurity j in the final water is then $\sum_{j=1}^{M} c_{ij}q_i$, and the concentration in the final water is $c_{ij}q_j/T$. This must be less than C_j, for every impurity j, or:

$$\frac{\sum_{j=1}^{M} c_{ij}q_i}{T} < C_j \quad (j = 1 \text{ to } M).$$

The entire problem can be stated mathematically as:

Minimize $\sum_{i=1}^{N} q_iK_i$, subject to:

$$\sum_{i=1}^{N} q_i \geq T$$

$$q_i \leq Q_i \qquad \text{(all i, i = 1 to N)}$$

$$\sum_{j=1}^{M} c_{ij}q_i/T \leq C_j \qquad \text{(all j, j = 1 to M)}$$

$$q_i \geq 0 \qquad \text{(all i, i = 1 to N)}$$

(The last constraint insures that no water is returned to any of the sources.)

This is a relatively simple linear programming problem which can easily be solved on any computer. Canned programs which will solve the problem are available.

The linear programming formulation is useful in that the solution also provides the cost savings available when any of the constraints are relaxed. Costs are given by the values of the dual variables associated with the solution. (Dual variables are specified automatically in all linear programming codes.) The duals associated with the Q_i constraints are the benefits associated with making additional water available at each source. The duals associated with the C_j constraints are the savings associated with relaxing the limitation placed on the concentration of any impurity allowed in the final water.

The difficulties inherent in this approach to the blending problem are many. It is assumed that the impurities in the water are nonreactive, i.e., no reduction in concentration of important impurities takes place because of physical or chemical interactions between the impurities, and no new impurities are formed by the combination of waters with different impurities. Further, and more important, it is assumed that the costs associated with drawing water from any source are directly proportional to the amount drawn from that source. This second assumption is very rarely true. In order to procure any water from a source, some minimum amount of money must be spent, and so generally it is not practical to obtain only very small quantities of water from a given source. Also, once this initial outlay has been made, additional water is available at generally lower cost per gallon per day. This phenomenon is due to economies of scale. Therefore,

the results obtained by linear programming methods are only approximations. These approximations are good only if substantial amounts of water derived from these sources are to be utilized.

An interesting and somewhat similar application of linear programming, which includes provisions for upgrading water quality, was presented by Bishop and Hendricks (10). The problem they addressed is analogous to the problem of "cascading reuse" presented in Chapter V, B, 1, b and 3, b, but broader in scope. In this technique, the difficulty of multiple quality parameters is circumvented by substituting costs of upgrading water quality between two consecutive uses. All uses within a given area are included. The problem is stated as follows:

Given that demands for water exceed primary supply, and that water may be imported or desalted, and knowing also (a) the amount of water required and wastewater generated by every class of water user; (b) the cost of upgrading one user's waste for the use of another, or for reuse; and (c) the cost of primary, imported, and desalted water available -- determine the least cost method of satisfying all water demands.

This formulation allows not only cascading water reuse, i.e., uses in which the water is reused without treatment (treatment costs in this case being zero), but also the upgrading of wastewater for reuse. The data necessary for the model are easily presented in tabular and

matrix form. Actual data for the Salt Lake City Area are presented by Bishop and Hendricks. The linear programming formulation can be conceived as follows:

Define:

C_{ij} = the cost of upgrading water from source i for use by user j

x_{ij} = the amount of water from source i used by user j (to be determined)

M = the number of sources

N = the number of users

A_i = the quantity of water available at source i

B_j = the amount of water required by user j.

A source i can be either primary supply, imported water, desalted water, or wastewater from a particular user. The linear programming formulation is:

Minimize $\sum_{i=1}^{M} \sum_{j=1}^{N} C_{ij}x_{ij}$, subject to:

$$\left.\begin{array}{ll} (1) & \sum_{j=1}^{N} x_{ij} \leq A_i \\ (2) & \sum_{i=1}^{M} x_{ij} \geq B_j \\ (3) & x_{ij} \geq 0 \end{array}\right) \quad \left(\begin{array}{l} i = 1 \text{ to } M \\ j = 1 \text{ to } N \end{array}\right.$$

The first set of constraints ensures that no more water is taken from a source than is available at that source, while the second set ensures that all water requirements are met. The third set of constraints forbids negative flow. The objective is simply to minimize total cost.

When the problem is presented in this simple form, a more efficient technique, called the transportation algorithm, can be used for its solution. However if, as Bishop and Hendricks suggest, combined intermediate treatment is to be used, and if a limit is put on the number of times water can be reused, then linear programming is appropriate.

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CHAPTER VIII. ECONOMIC TECHNIQUES FOR OPTIMAL WASTE AND RECEIVING-WATER PURIFICATION

To the economic techniques reviewed in Chapter VII for optimizing water supply enhancement and allocation are now added techniques pertaining to the optimal solution of the pollution problem. In need of purification are both wastes and receiving waters. The latter are likely to be used again for water supply and, at any rate, lakes, rivers, and estuaries serve as bases for recreation, habitats for aquatic life, and settings for aesthetic enjoyment.

Four problems are discussed below: waste disposal, effluent charges and control, receiving-water quality management, and optimal waste treatment.

A. Waste Disposal

Because waste disposal in streams and lakes has not generally been subject to charges, the demand for such services has met no constraints. With enforced water quality standards or waste disposal charges, the demand would not surpass the waste permitted by the standards, or would tend to settle around an optimum level responsive to waste disposal cost changes. In many areas, the present demand exceeds both of these levels.

Brown and Mar (1) looked into the externalities of waste disposal. Damages incurred by water users because of pollution in excess

of the constraints that would be provided by standards or charges are of three types: some damages (as to water supply) decrease linearly with concentration; others (as to fish and wildlife) are reduced sharply at a given threshold concentration; the balance (as to navigation, or industrial cooling) are essentially independent of water quality. The aggregate damage (or loss-of-benefit) function has the shape of an asymptote, and the marginal damage function is bell-shaped.

By means of data on waste discharges (conservative contaminants affect water quality linearly; non-conservative pollutants, non-linearly), the waste disposal demand function, the damage function, marginal benefits, and marginal treatment costs, the authors state that it becomes possible to determine the optimum level of waste discharges. For economic efficiency, standards or charges should be set to coincide with that level.

B. Effluent Charges and Control

Effluent charges as a means of meeting water quality standards have been proposed chiefly by Kneese (2), and Kneese and Bower (3). The development of the theory of effluent charges presented here is after Brill (4).

An effluent charge is taken to be a monetary charge imposed on a municipal or industrial waste discharger by a governmental authority

to provide an incentive for waste reduction. The units of the charge are \$/waste unit. Total effluent charges are increasing functions of the amount of waste discharged. Such charges are at a maximum if waste is not reduced below an initial level. As waste is reduced, the charge payment decreases and savings result. Total savings are a function of waste reduction.

Consider, for example, a total effluent charge function which increases linearly with increasing waste discharge. Define:

TCh = total effluent charge (\$/day)

g = constant unit charge (\$/waste unit)

FD = initial waste discharge (lb/day of waste)

f = waste reduction below initial level (lb/day of waste)

TS = total savings

The total effluent charge function TCh equals g(FD-f). The maximum charge is given by: $TCh_{max} = g(FD)$. And total savings equal: $TS = TCh_{max} - TCh = gf$. Standard economic theory indicates that a discharger will reduce his discharge to the point where marginal savings equal marginal costs.

If the marginal cost curves of all dischargers are known, the uniform effluent charge which will cause polluters to reduce their discharges just enough to meet a given water quality standard can be determined in a manner analogous to finding the minimum level

uniform treatment which just meets a standard. Try a charge and compute the results. If results are too high or too low, try a lower or higher charge. If the marginal cost curves are not known, determining the lowest charge is considerably more difficult. Alternative means have been suggested, however, by Haas (14) and Taylor (15).

Baumol and Oates (16) have shown that, for conservative pollutants, uniform effluent charges can be used to insure compliance with water quality standards at minimum cost to the economy. That is, imposition of effluent charges is a Pareto-optimal means of achieving water quality standards for conservative pollutants. They compare the effluent charge method to other methods for achieving water quality objectives and show it to be readily workable. For non-conservative pollutants such as heat and BOD, uniform effluent charge schemes are generally not Pareto optimal.

Brill (4) compares many different effluent charge schemes for inducing polluters to reduce their own BOD loading on the Delaware, both as to equity (as viewed by the dischargers) and economic efficiency. He separates the costs paid by the dischargers to reduce the quantity of their discharge from the effluent charges they pay to the government. The sum of the two, he calls the financial burden borne by the discharger; only the first represents social costs of pollution control, the second being a transfer of income from the discharger to the government -- so long as the latter does not provide collective treatment.

Brill investigates effluent charge schemes which reduce social cost, and also schemes which reduce the financial burden on the dischargers.

C. Receiving-Water Quality Management

Many recent papers have addressed the problem of meeting instream water quality objectives. In most instances, what is meant is the maintenance of preset levels of dissolved oxygen in a stream. Nearly all of the papers reviewed make use of some form of the Streeter-Phelps model of dissolved oxygen deficits. Discussion of the model, developed below, is after Metcalf & Eddy (5).

Organic materials in streams are oxidized by bacteria. These breathe DO as they grow. As oxygen is used, the concentration of DO in the stream is reduced. On the other hand, DO enters the stream by diffusion and mixing at the surface, and through algal growth. These processes can be described methematically.

Define:

C_s = temperature-dependent saturation concentratior of oxygen

C = actual time-varying concentration of oxygen in the stream

C_o = concentration of oxygen in the stream at time zero

D = oxygen deficit

K_1 = constant called the bio-oxidation rate

K_2 = constant called the reaeration rate

L = concentration of BOD in the stream

L_o = incremental BOD load in the stream

t = time

The rate of oxygen uptake by bacteria equals the bio-oxidation rate multiplied by the BOD load:

$$\frac{dC'}{dt} = K_1 L$$

The reduction in the BOD load in the stream is equivalent to the amount of oxygen uptake by bacteria:

$$\frac{dL}{dt} = K_1 L = \frac{dC'}{dt}$$

As the bacteria remove oxygen, DO also enters the stream by diffusion, mixing, and algal growth, at a rate equaling the reaeration rate multiplied by the oxygen deficit:

$$\frac{dC''}{dt} = K_2 D$$

The overall rate of change in oxygen concentration is the difference between the two preceding terms:

$$\frac{dC}{dt} = K_2 D - K_1 L$$

When the above equations are solved for D, the classical Streeter-Phelps equation results:

$$D = \frac{K_1 L_o}{K_2 - K_1} (e^{-K_1 t} - e^{-K_2 t}) + (C_s - C_o) e^{-K_2 t}.$$

Being a linear function of L_o, D is suitable for use in linear programming models for minimizing cost. Pioneering work in the formulation of such models has been performed by Deininger (6), ReVelle, Loucks and Lynn (7), and Liebman (8). The latter presented a dynamic program. ReVelle, Loucks and Lynn, in another writing (9), comparing dynamic and linear programming, found both methods led to similar results.

D. Optimal Waste Treatment

We are now coming to grips with the waste discharger and with linear programs designed to optimize effluent treatment. To prevent non-linearities in cost curves, some minimum amount of treatment is usually required of all dischargers. Costs of treatment, beyond primary, increase at an accelerating rate with the percent of BOD removed.

From the Streeter-Phelps equation can be derived the water quality improvement in a reach of a stream resulting from a unit waste reduction by a discharger. A linear programming model can now be written. Brill's (4) formulation is equivalent to, and simpler than, many others:

Define:

N = number of dischargers

j = identification of the discharger

i = identification of the reach of the stream

k = identification of a particular value of reduction

f_j = amount of reduction by discharger j (unknown)

$C_j(f_j)$ = total cost of f_j

K_j = total number of specific values of reduction by discharger j

A_{ij} = water quality improvement in reach i resulting from a unit waste reduction by discharger j

B_i = required water quality improvement in reach i

M = number of reaches with water quality improvement goals

U_{jk} = a particular value of f_j, the reduction by discharger j (known)

FT_j = total waste production by discharger j

Z_{jk} = a weight associated with a particular reduction U_{jk} (unknown)

The function to be minimized is total cost:

$$\text{Min} \sum_{j=1}^{N} \sum_{k=1}^{K_j} C_j(U_{jk})Z_{jk}, \qquad \text{subject to:}$$

$$\left.\begin{array}{ll}
(1) & \displaystyle\sum_{j=1}^{N} A_{ij} \cdot f_j \geq B_i \\
(2) & \displaystyle\sum_{k=1}^{K_j} Z_{jk} \leq 1 \\
(3) & (1/FT_j) \cdot f_j \geq 0.35 \\
(4) & \displaystyle\sum_{k=1}^{K_j} Z_{jk}U_{jk} = f_j
\end{array}\right) \quad \begin{array}{l}(\; i = 1 \text{ to } M \\ (\\ (\; j = 1 \text{ to } N\end{array}$$

The first constraint ensures that all water quality improvement goals are met. The second, that the solution follows the cost curve. The third constraint makes certain that each discharger will provide at least 35% removal of waste (primary treatment). The last defines f_j in terms of the weight variable Z_{jk}.

The solution to this linear programming problem provides the least cost means of treating all wastes at the point of discharge. No other types of treatment are considered. The model is entirely deterministic, and if no contraventions to given standards are allowed, the A_{ij}'s are defined by the worst possible conditions. Not surprisingly, many authors have proposed improvements to the basic model just presented. These are discussed below.

One of the major difficulties with the model just presented is that it often seems quite inequitable to those who must bear the cost of waste treatment. In the least cost solution, it is not uncommon to find that one discharger will have to remove a high proportion of his wastes while a neighbor will have to institute only a moderate reduction at much lower cost. It can be very difficult to implement least cost solutions which are perceived as inequitable. The Delaware Estuary Comprehensive Study (10), recognizing this difficulty, proposed that

the Delaware Estuary be divided into zones, and that each discharger within a given zone be required to provide the same level of treatment. While this scheme is considerably less costly than requiring a single level of treatment of all dischargers on a stream, it is still more costly than the lowest least-cost solution described above. Uniform treatment solutions, so called because every discharger is required to institute the same level of treatment, are generally the most expensive of all means for meeting a given instream water quality requirement.

It is relatively easy to find the minimum level of uniform treatment which will satisfy a water quality requirement. A search technique can be utilized. Simply try any level of treatment and solve for the resulting water quality. If the quality exceeds the required quality, try a lower level of treatment. If the quality is lower than required, try a higher treatment level. The process is repeated until one is sufficiently close to meeting the requirement. The last level tried is optimal. Any policy which requires a higher level of uniform treatment than that arrived at by the above procedure is satisfying goals other than for water quality. Thomann (11) considers a wide variety of alternative management programs which do satisfy water quality goals and trade social and political considerations against cost.

Liebman and Marks (19) have proposed an integer programming formulation of the problem of deciding how best to divide a river into zones

so that a zoned uniform treatment program such as proposed by the Delaware Estuary Comprehensive Study may be implemented at least cost. Basically, the problem to be solved is one of drawing the lines that determine which discharge is in which zone for any given number of zones. The larger the number of possible zones, the lower the cost of the optimal solution.

Brill (4), in his doctoral dissertation, has examined in great detail questions of equity. He shows that in the case of the Delaware Estuary, the cost of the optimal solution can be greatly reduced by requiring high levels of treatment of only very few dischargers, and suggests that equity considerations might be satisfied if some agreement could be reached whereby those dischargers with only modest treatment requirements would subsidize those of whom higher levels are required. For a discussion of waste control cost allocation, see Chapter V, D.

Graves, Hatfield and Whinston (12), using a linear programming model of the Delaware Estuary, solved the pollution problem without any treatment being needed, simply (as suggested in Chapter V, A, 2) through longitudinal staggering of outfalls in by-pass piping. While the approach proposed by the authors for the Delaware considers only BOD, such a system of releases might also be of value in reducing treatment costs for some other stream contaminants.

Expanding the study in a recent sequel, Graves and Hatfield (13) considered a variety of alternative technological options for pollution

control in an overall optimization. While the zoned uniform treatment plan (all treatment at the source) now favored by the Delaware River Basin Commission would cost $8.2 million annually, and while the least-cost solution for treatment at the source provided by a linear program would reduce the cost to $4 million annually, Graves and Hatfield's optimal solution, using treatment at the source and at collective facilities plus longitudinally staggered outfalls, brought the cost down to $2.3 million per year. Details are mentioned in Chapter V, A, 2.

Models have also been proposed for minimizing the cost of electrical power generation subject to water quality standards concerning excess temperature. Marks and Borenstein (17) present three models for the optimal siting of thermal electric generating stations, which strike balances between the costs of power production and transmission to load centers and the costs of complying with temperature standards. The models are intended to serve as aids in making location decisions, particularly by showing the sensitivity of solutions to changes in input parameters, and by permitting evaluation of cost changes associated with different siting policies and different temperature standards. Of the models presented, only the 0-1 linear integer programming model is treated in depth. A solution technique for this model is presented which is applicable to problems of moderate size. A sample problem is formulated. Marks (18) has used these methods to solve a siting problem in Connecticut.

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